COMPARISON OF TECHNOLOGIES TO DETERMINE RHODAMINE CONCENTRATION IN STREAMS

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Abstract

Time-of-travel studies using rhodamine dye are often performed in streams to determine parameters pertinent to hydraulic modeling. New technologies for determining the concentration of the dye in-situ are being developed by Yellow Springs Instruments, Incorporated (YSI). The goal of this study was to evaluate the new in-situ probes in comparison with the industry-standard conventional field fluorometer and determine whether these new probes sufficiently captured the dye plume. Dye was injected into the Big Walnut Creek and Alum Creek in Central Ohio. Grab samples of stream water were taken from bridges downstream and evaluated using a Turner Instruments fluorometer. Simultaneously, YSI datasondes with rhodamine sensors were installed in the stream and continuously logged the concentration. The time-of-travel studies were performed under high and low flow conditions. It was determined that the YSI continuous sampler performed well once a background level was subtracted from the data. However, the background level to subtract would not be known unless a conventional fluorometer was also used. This background may be due to interference caused by algae concentrations in the stream and possibly some turbidity impacts. Therefore, the optical filter used by the YSI sensors in this study must be tuned specifically for rhodamine in order for reliable hydraulic information to be obtained from the sensor.

Introduction

Dyes are used in streams to determine hydraulic characteristics because they behave the same way that water does, making it an ideal tracer. Because the dye will flow the way that water flows in the stream, measurement of how the dye moves is also a measurement of how water moves in the stream (Kilpatrick and Wilson 1989). Rhodamine WT is the dye used in this study, and is the recommended dye to be used in determining hydraulic characteristics of streams according to the United States Geological Survey (USGS). (Kilpatrick and Wilson, 1989). Rhodamine WT dye is bright magenta in color and is used because it does not readily react with particles in the water. Other dyes such as fluorescein, sodium chloride, potassium chloride and tritium are used less frequently because of their higher reactivity rates (www.turnerdesigns.com, 2002).

Data collected from a dye study can be used for various purposes. Most commonly, dye studies are performed to determine the amount of time required for dissolved constituents in the stream to travel to downstream sites, and to observe how those constituents will disperse in the stream (Chapra, 1997). Methods such as determining discharge in small channels can be found using dye (Kilpatrick & Cobb 1985). Kilpatrick et al. (1989) described methods to measure oxygen absorption, or reaeration, using dye. Kilpatrick (1993) detailed a variety of waterbodies that can be studied and parameters that can be determined using a dye study. There is also modeling software such as the U. S. Environmental Protection Agency's Water Quality Analysis Simulation Program (EPA WASP) which will simulate an injection of dye so that

hydraulic parameters such as dispersion and velocity in a stream reach can be determined (Wool et al., 2001).

A dye study can be beneficial for water quality studies in two ways. First, a dye study significantly increases the understanding of the hydraulics of a stream. Instead of studying and surveying discrete sections of a stream, a dye study gives quantifiable information over the length of a stream. These parameters could be used to represent the hydraulic characteristics of a water quality stream model. Second, the movement of dye mimics how pollutants move through the stream. For example, if a tanker truck full of gasoline spilled its contents into a stream, a dye study would give valuable information on how the gasoline might move downstream. Emergency crews could predict how long it would take for the gasoline plume to reach downstream water treatment plant intakes using the information collected from a dye study.

The USGS developed most of the prior research and standards for completing dye studies. Jobson (1997) commented that in order for dispersion and velocity models to give more accurate predictions, reliable input from the stream is needed. A dye study is very effective in determining the desired parameters for these models. A number of articles published by the USGS are assembled as a series of books entitled *Techniques of Water Resources Investigations of the United States Geological Survey* (TWI). Book 3 of the TWI series contains most of the information available on dye studies. Methods of measuring concentration, field and equipment information (Kilpatrick and Wilson, 1989), and types of dye and fluorometers (Wilson et al., 1986) are described.

The industry-standard fluorometer Turner Designs Model 10-AU-005-CE used in this study is commonly used in dye studies. The fluorometer works by passing an

excitation light through a special filter and into the sample. When light enters a sample with fluorescent molecules such as rhodamine WT, light is reflected from the particles at an altered, longer wavelength. The amount of reflection is proportional to the concentration of the rhodamine in the sample and the intensity of the exciting light (Turner Designs). The fluorometer then displays the concentration of the dye in the sample based on the amount of altered reflected light.

Today, accuracy in rhodamine dye studies is especially important. The determination of accurate hydraulic parameters is important to the development of correct water quality models (Jobson, 1997). There is a growing need to understand the movement of water in streams, as well as other bodies of water that receive waste loads from point sources. These hydraulic parameters help determine the assimilative capacity of the waterbody for the loads entering the receiving body. Therefore accurate hydraulic parameters are vital in the development of values for Total Maximum Daily Loads (TMDLs) for point sources and for permit compliance under the National Pollutant Discharge Elimination System (NPDES). These regulatory requirements were a major motivation for Yellow Springs Instruments, Incorporated (YSI) to develop a rhodamine sensor that could be easily used with YSI datasondes to collect continuous, reliable rhodamine concentration information (www.ysi.com, 2003).

The new prototype YSI probe changes the way that rhodamine is sampled. The rhodamine probe installs directly into the optical sensor port of many YSI datasonde water quality probes. This means that the entire probe and sensor can be submerged directly into the water column. Because a datasonde is used, more dye concentrations can be recorded, and at a rate more frequent than is possible with grab sampling followed

by analysis with a bench fluorometer. In addition, samples no longer have to be physically removed from the water body to be evaluated. This new technology allows for safer, less resource intensive field conditions, and less room for human error in sample collection (www.ysi.com, 2003).

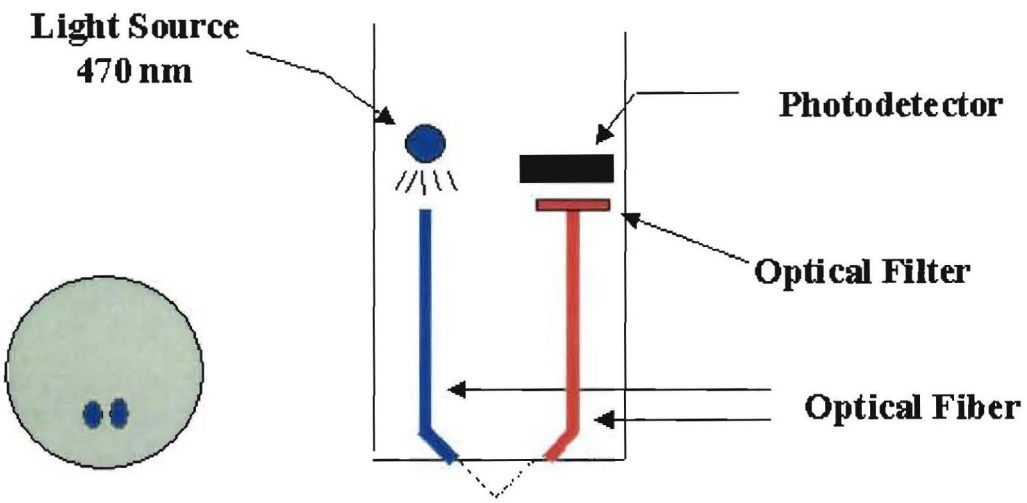

Figure 1: Schematic of Chlorophyll Sensor Operation (www.ysi.com, 2003)

The YSI rhodamine sensor operates much like the standard fluorometer. Figure 1 shows schematics of the probe. The probe works by emitting light in the blue-green wavelength into the water column through one port at the bottom of the sensor. This light reflects off of the fluorescent rhodamine in the water column, and is collected in the second port on the sensor. This light passes through an optical filter and onto a photodetector that determines the amount of light reflected, which represents the concentration of dye in the stream (www.ysi.com, 2003). A picture of the final design is shown in Figure 2.

Figure 2: YSI Rhodamine Sensor (www.ysi.com, 2003)

The rhodamine probe developed by YSI began as a modification of the previously developed YSI chlorophyll sensor. Because of the similar fluorescent properties of chlorophyll and rhodamine, the only significant adjustments that would be needed were changes in the optical filter of the chlorophyll sensor so that only reflectance from rhodamine molecules would be detected.

Although these new technologies offer many benefits when performing studies using fluorescent materials, these probes are still in the process of development and need to be evaluated in comparison to the standard fluorometer to test their accuracy. The goal of this study was to evaluate the new in-situ rhodamine probes in comparison with the conventional field fluorometer and determine whether these new probes sufficiently captured dye concentrations. This evaluation was performed while completing time-of-travel studies on the Big Walnut and Alum Creeks in the Central Ohio area.

Methods

Two dye studies were performed on the Big Walnut and Alum Creeks: one during high flow, and one during low flow. In each study, a measured volume of dye was injected into the center of the channel from a bridge over the stream. The sampling sites were off of bridges located downstream of the dye injection point (See Appendix A). Water samples were collected from the center of the channel by a bucket lowered over the bridge. To determine dye concentration, grab samples were placed in cuvettes and analyzed using a Turner Designs Model 10-AU fluorometer with a rhodamine optical filter. The concentration of rhodamine, temperature, and time of sampling were recorded for the discrete samples. Dye concentration was also measured using a YSI datasonde with a chlorophyll sensor modified to detect rhodamine concentration. The datasondes were installed directly into the center of the channel below the bridge and recorded water temperature, conductivity, turbidity, dye concentration, and time at a specified interval ranging from every minute to every fifteen minutes.

Once the rhodamine dye arrived at the sampling site, grab samples were collected and analyzed using the Turner Designs fluorometer. Grab samples were taken from the bridge by lowering a bucket into the stream and pulling the sample of stream water up in the bucket using a rope. A cuvette was filled with the stream water from the bucket. The cuvette was cleaned using a Kim-Wipe tissue and placed in the fluorometer. The concentration of fluorescent dye in the sample was displayed on the fluorometer and recorded in the field book along with the time that the sample was collected. After most, or all, of the dye plume had passed, the YSI datasonde was removed from the stream and placed at another sampling site further downstream. The discrete sampling continued at

Assume Missing Page 8

Once collected, the data was normalized for temperature. Rhodamine concentration was modified to account for temperature of the sample according to an equation supplied by Turner Designs (www.turnerdesigns.com, 2002):

$$F_r = F_s \, e^{(n(T_s - T_r))}$$

The correction equation considers the temperature at which the fluorometer was calibrated (Tr), the sample temperature (Ts) and fluorescence (Fs) of the sample, and the temperature coefficient for the dye, 0.026 (n). Applied to the data, this equation gives the temperature-corrected concentration of dye in the sample.

The YSI chlorophyll sensor data was also temperature corrected using the above equation. In order to correct for the turbidity, algae, and other interferences with the YSI probe, a background concentration was adjusted from each data set so that it more accurately fit the Turner Designs sample data. This "background" ranged from adding 37 to subtracting 62 ppb (parts per billion or ug/L) of rhodamine across both the dry and wet weather studies. Some texts suggest subtracting 3 ppb of rhodamine for every 100 NTU (National Turbidity Units) observed. This ratio largely results in curves that are still significantly higher than the curves developed by the Turner Designs fluorometer readings for the same site. It is believed that other factors such as algae may be causing interference with the chlorophyll probes on the YSI Sondes.

The data collected were compared against each other to determine whether there was a significant difference between the prototype rhodamine probes and the industry-standard fluorometer. Only data points that were collected at the same time were compared in this study. ANOVA statistical tests were performed on the data to

determine if there was significant statistical similarity. Raw data and background-adjusted data were compared so that typical background interference could be determined. This "background" is most likely the result of an optical filter that is not in its final stage of development in the prototype probe, because the optic filter was not completely tuned specifically for rhodamine. Because of this, turbidity and chlorophyll in the water column will contribute to a background but appear as a heightened rhodamine concentration (www.ysi.com, 2003).

Results

Dry Weather Data

Before the background level was subtracted from the YSI data there was significant difference between the YSI and fluorometer data (average P=0.124). Figure 3 is a sample of a dry weather event containing the temperature corrected data from the YSI datasonde and the temperature corrected fluorometer grab samples. Appendix B contains all of the figures displaying the curves before the background level was subtracted.

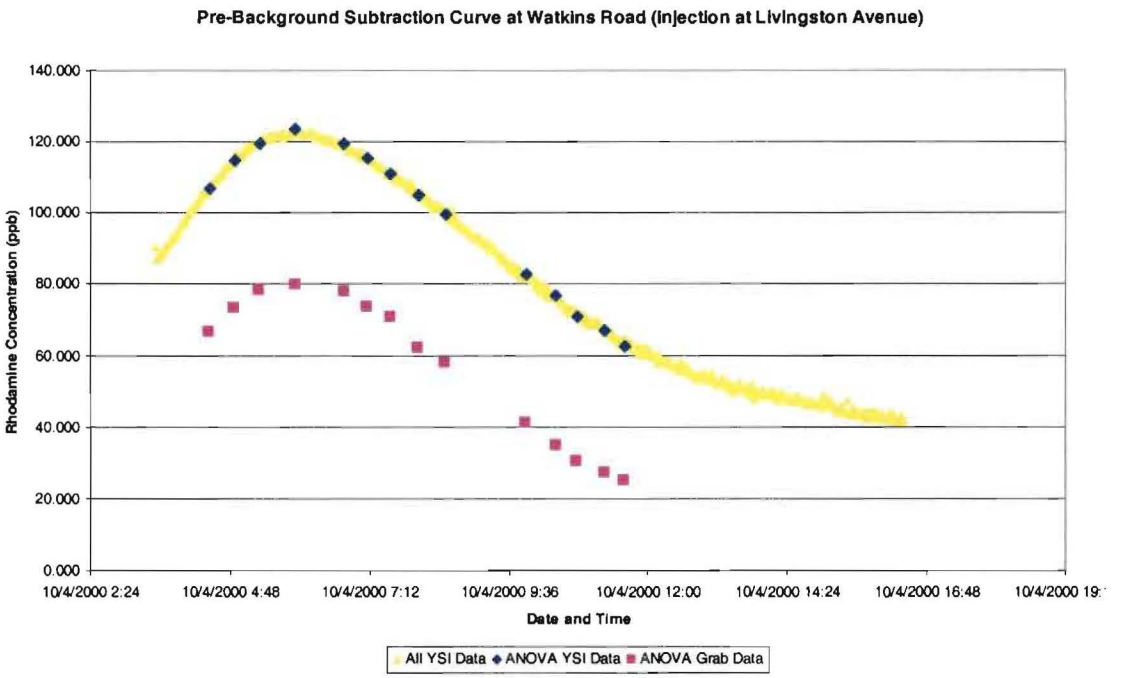

Figure 3: Dry Weather Dye Study curves with Temperature Corrected Data and No Background Subtraction

Figure 4 shows the data from Figure 3 that has a background concentration value (41 ug/L) subtracted from the data. The average background level subtracted from all of the dry weather YSI samples was 33.21 ug/L. The background level subtracted from the YSI data ranged from 1 to 44 ug/L. The adjusted YSI data had a very strong correlation to the fluorometer data (average P=0.979). Table 1 displays all of the sites where YSI data and fluorometer data were collected. In the table, the injection site and sampling site are displayed as well as the background level subtracted and correlation values between the YSI and fluorometer data before and after YSI adjustment. Appendix B presents all of the figures displaying the curves after the background level was subtracted.

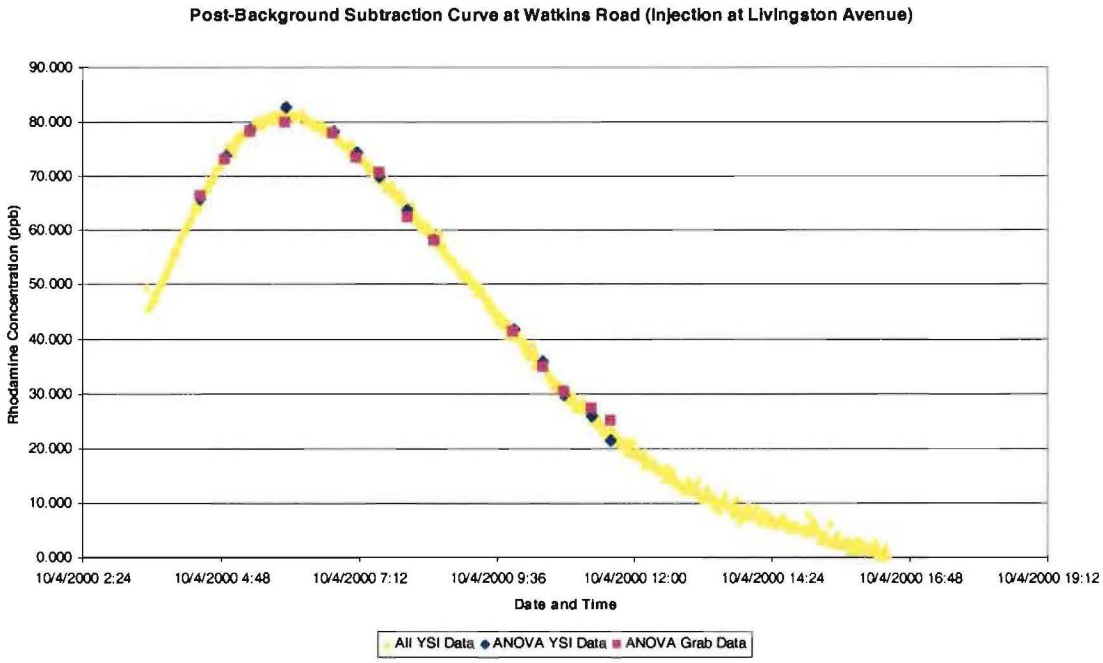

Figure 4: Dry Weather Dye Study curves with Temperature Corrected Data and Background Subtraction

Table 1: ANOVA Comparisons of Dry Weather YSI and Fluorometer Data

Injection Site	Sampling Site	Number of Intersecting Data Points	P-Value	Background Subtraction	New P-Value
Watkins	Williams	33	2.08E-04	42	0.982
SR 317	SR 23	6	4.08E-03	31.5	0.992
SR 317	Rowe	22	4.21E-05	33	0.989
SR 161	Innis	9	7.41E-02	32	0.987
SR 161	Morse	14	8.22E-02	44	0.986
Reese	SR 317	30	5.79E-12	37	0.990
Reese	Lockborne	12	9.58E-02	32	0.996
Main	Route 3	12	2.83E-01	22	0.982
Main	Schrock	18	3.30E-01	29	0.998
Livingston	Watkins	14	2.43E-05	41	0.991
Livingston	SR 104	16	1.63E-02	34.5	0.990
Innis	Mock	16	2.26E-01	30	0.976
Innis	Agler	8	4.93E-01	38	0.973
Footbridge	Reese	41	4.66E-01	1	0.854
Airport	Livingston	18	1.04E-08	40.5	0.993
Airport	Wolfe Park	6	1.67E-02	35	0.984
Airport	Clifton	11	2.44E-02	42	0.984
Average			1.24E-01	33.21	0.979
Minimum			5.79E-12	1.00	0.854
Maximum			4.93E-01	44.00	0.998

Wet Weather Data

Before the background level of the YSI data was adjusted there was significant difference between the YSI and fluorometer data (average P=0.318). Figure 5 is a sample of a wet weather event containing the raw data from the YSI datasonde and the fluorometer grab samples. All of the figures displaying the curves before the background level was adjusted can be seen in Appendix C.

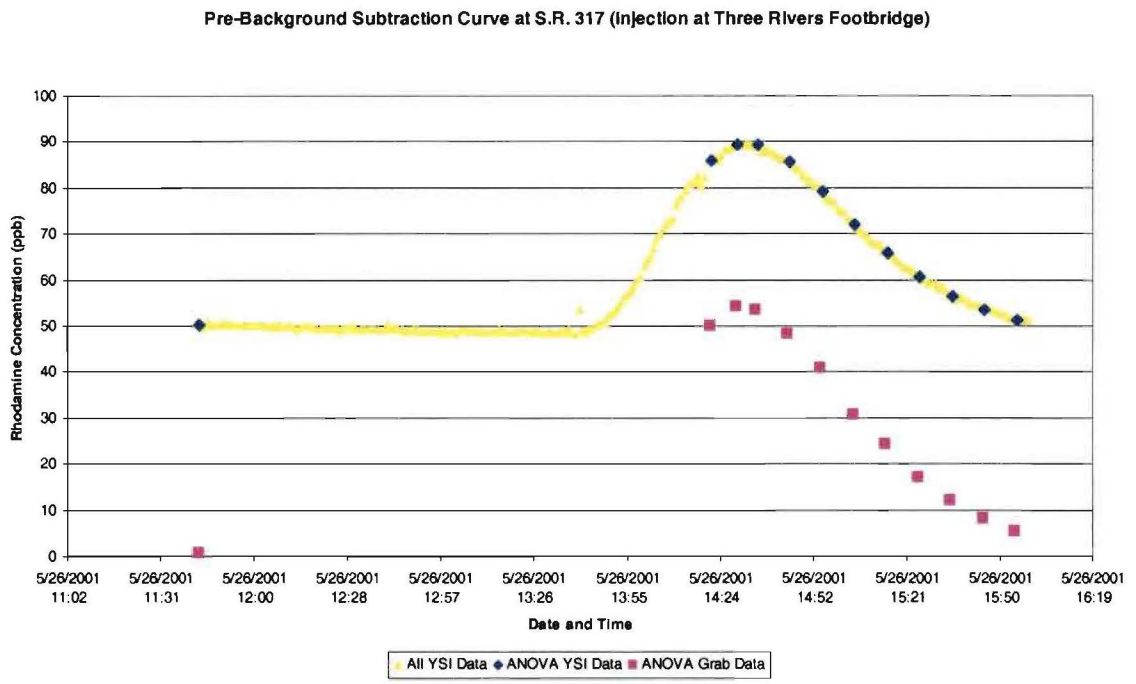

Figure 5: Wet Weather Dye Study curves with Temperature Corrected Data and No Background Adjustment

Figure 6 shows the data from Figure 5 that has a background (41 ug/L) subtracted from the data. The wet weather samples did not always need a background subtraction. In some instances a background had to be added to the YSI dataset to obtain the best correlation in the datasets. The backround adjustment ranged from adding 37 ug/L to

subtracting 62 ug/L. The average adjustment for all of the wet weather data sets was a subtraction of 18.75 ug/L (or -18.75 ug/L). The adjusted YSI data had a very strong correlation to the fluorometer data (average P=0.985). Table 2 displays all of the sites where YSI data and fluorometer data were collected. In the table the injection site and sampling site are displayed as well as the background level subtracted and correlation values between the YSI and fluorometer data before and after YSI adjustment. Appendix C contains all of the figures displaying the curves after the background level was adjusted.

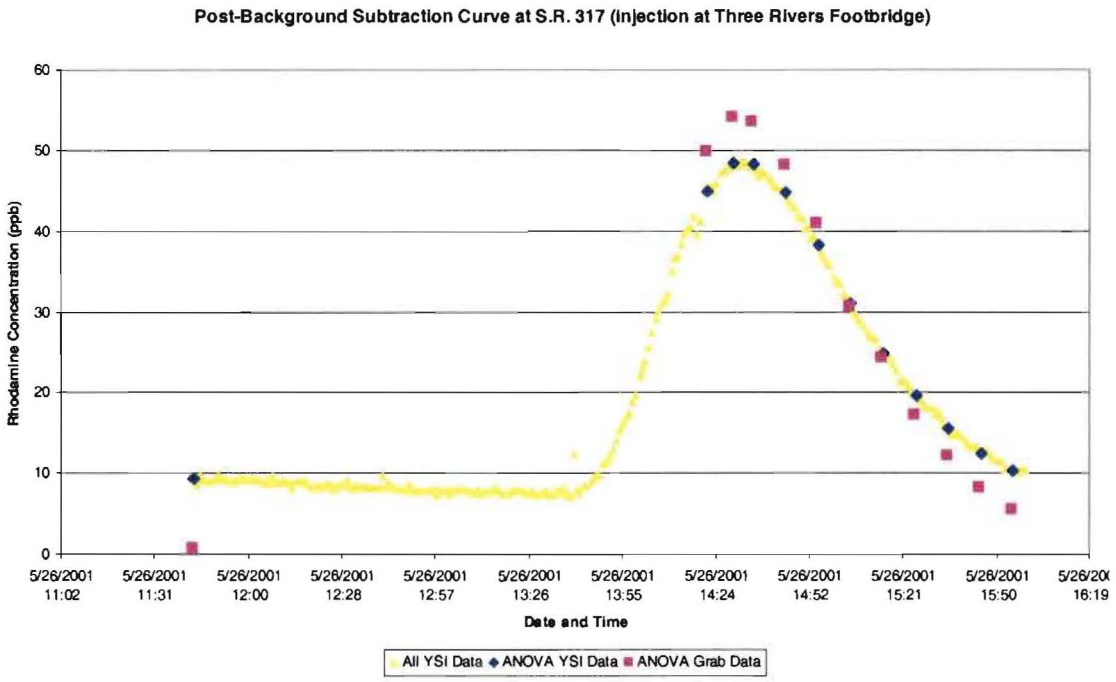

Figure 6: Wet *Weather Dye Study curves with Temperature Corrected Data and Background Adjustment*

Table 2: Results of ANOVA Comparisons of Wet Weather YSI and Fluorometer Data

Injection Site	Sampling Site	Number of Intersecting Data Points	P-Value	Background Subtraction	New P-Value
Footbridge	SR 317	12	1.142E-05	-41	0.977
Footbridge	Reese	13	1.450E-02	-33	0.996
Footbridge	Groveport	21	2.429E-01	-26	0.988
Mock	Groveport	3	1.706E-04	-33	0.930
Mock	Williams	10	5.846E-01	-11	0.982
Mock	Watkins	2	2.565E-01	4	0.968
Mock	SR 104	2	3.434E-01	-17.5	0.992
Mock	Livingston	14	7.664E-01	7	0.991
Mock	Clifton	9	9.685E-01	-2	0.999
Mock	Airport	13	6.589E-01	26	0.996
Main	Airport	17	7.242E-04	-41.5	0.999
Main	Innis	4	1.506E-01	-42	0.995
Main	Morse	8	4.894E-01	-21	0.989
Main	SR 161	2	2.030E-02	-62	0.971
Main	Route 3	5	6.850E-02	-44	0.983
Main	Schrock	11	5.206E-01	37	0.999
Average			3.179E-01	-18.75	0.985
Minimum			1.142E-05	-62.00	0.930
Maximum			9.685E-01	37.00	0.999

Discussion

The prototype rhodamine sensor YSI developed was a modification to the chlorophyll probe that YSI currently had on the market. The rhodamine sensor differs from the chlorophyll sensor only by the optical filter used in the probe. Compared to the chlorophyll sensor, the rhodamine sensor was more specifically tuned to pick up the specific wavelength of light reflected from a rhodamine molecule in the water. However, because these rhodamine sensors are indeed prototypes, this test was performed to compare how these upgraded chlorophyll sensors compared to the Turner Instruments field fluorometer.

Dry Weather Data

The dry weather time-of-travel studies occurred in a period of low, or base, flow for the stream. Low flow conditions in the stream are typically less turbid in comparison to high flow levels. However in every data set collected from the YSI sensor a background level had to be subtracted. This could be due to a relatively high turbidity or more likely, a high algae population in the stream under normal conditions, which lead to the interference observed in the rhodamine readings. This high background of turbidity and chlorophyll in the stream was supported by the high correlation between the fluorometer and YSI data after a background is subtracted.

The interference of turbidity and chlorophyll in the prototype rhodamine sensor makes the concentrations of rhodamine reported by the probe unreliable. Therefore, the prototype YSI sensor cannot solely be used to determine detailed hydraulic characteristics of a stream such as dispersion. If these parameters are desired, a field fluorometer must also be used with the YSI prototype sensors so that the YSI sensor data is accurately adjusted to report the most correct concentration of rhodamine in the stream channel. Nevertheless, it should be noted that the YSI data clearly defined peaks and was sufficient to determine time-of-travel in the stream. The trend of the data reported by the YSI sensor was correct, but the magnitude of the data was inaccurate.

In order for the prototype sensor to report meaningful data, it was determined that the optical filter would require modification so that only light reflected from the fluorescent rhodamine in the water column was transmitted to the photodetector (See Figure 1 above). If the optical filter were adjusted in this manner, the need for a field fluorometer to confirm the rhodamine concentration may be unnecessary. Further

research comparing any new updates to sensors and the industry-standard fluorometers would be warranted.

Wet Weather Data

The wet weather time-of-travel studies occurred in a period of rainfall, causing high flow in the stream. High flow conditions in the stream create turbulence and the water becomes typically more turbid in comparison to low flow levels. The expected effect of these more turbid conditions is that the YSI rhodamine sensor will have a significantly higher background level in comparison to the dry weather data. However, this did not occur in all trials. In two of the studies performed, a background level had to be added to the YSI sensor data to match best with the fluorometer data.

It is possible that only chlorophyll had an influence on the sensor, and that turbidity did not play a large role in the background level of the dry weather data. The high flow conditions would cause much of the suspended and attached algae in the stream to be carried downstream.

Once the necessary adjustments were made to the YSI data points, the curves still fit well with the fluorometer data. However, because of the randomness of the background levels these sensors were not found reliable if used alone during high flow conditions. Again, it is recommended that if these sensors are implemented that they be used in conjunction with a fluorometer so that the correct "background" adjustment for the YSI datapoints may be made. Based on the results of the wet weather data, it is suggested that the optic sensor used in the probe be tuned more specifically for the light reflected from the rhodamine in the water column so that background levels would be eliminated.

Conclusions

The YSI rhodamine sensor under development will change the way that rhodamine time-of-travel studies are performed for the better. These probes are easily installed on the YSI datasonde, can take readings at one minute intervals, and are submersible. This new technology greatly reduces the amount of time and resources necessary for the typical fluorometer time-of-travel study (www.ysi.com, 2003). However this study shows that these modified chlorophyll sensors will need more modifications before they are the sole instruments used in the field.

The prototype sensors may be valuable if only general, relative trends need to be observed in the stream. For example, if the time of travel between sampling sites is all that needs to be determined, then the peak concentrations would be sufficient. It was observed that the data collected from the sensor clearly defines a peak. However, if the dispersion is a desired parameter to be calculated from the data, the concentration and the shape of the curve become very important and this prototype probe alone would not be sufficient. This study observed that chlorophyll interactions influenced the concentration and shape of the curves, rendering the YSI prototype sensor to be unreliable for this purpose.

Further Studies

After the data collected in this study were presented to YSI, further modifications were made to their rhodamine sensors and these new sensors have been proven to be more reliable in the field. The sensor software was programmed internally to correct the dye concentration with relation to temperature. These updated sensors are now sold by YSI, and another time of travel study was performed using these rhodamine-specific

sensors. The study took place in Hunters Run, a small stream to the west of Lancaster, Ohio. The results from this study can be found in Appendix D and Figure 7.

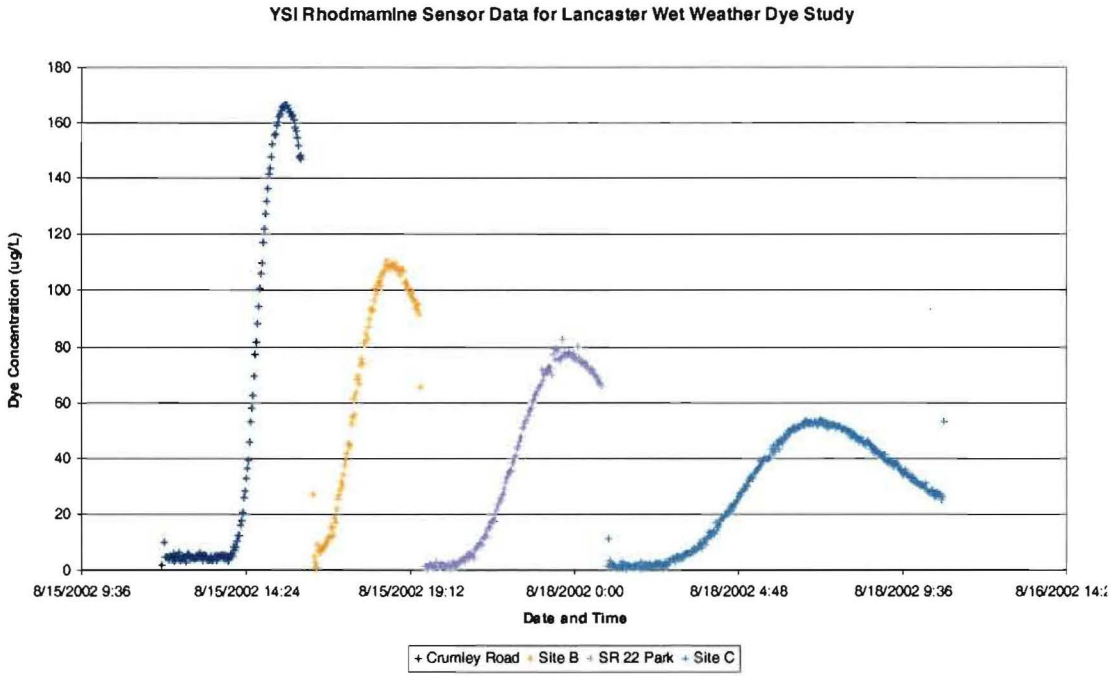

Figure 7: Wet Weather Dye Study Curves with Updated Rhodamine Sensors Integrating Temperature Correction and Needing No Background Adjustment

The curves collected in the Lancaster dye studies show much improvement in comparison with the prototype sensors explored in this study. The data collected with the prototype sensors and the fluorometer provided the information necessary for YSI to make the correct modifications to the optic sensor. Also, suggestions such as internally correcting for temperature were also included in the final design of the rhodamine probe. This study helped YSI to develop new technology that generates larger volumes of accurate data at a lower labor cost than was possible with the use of a standard field fluorometer.

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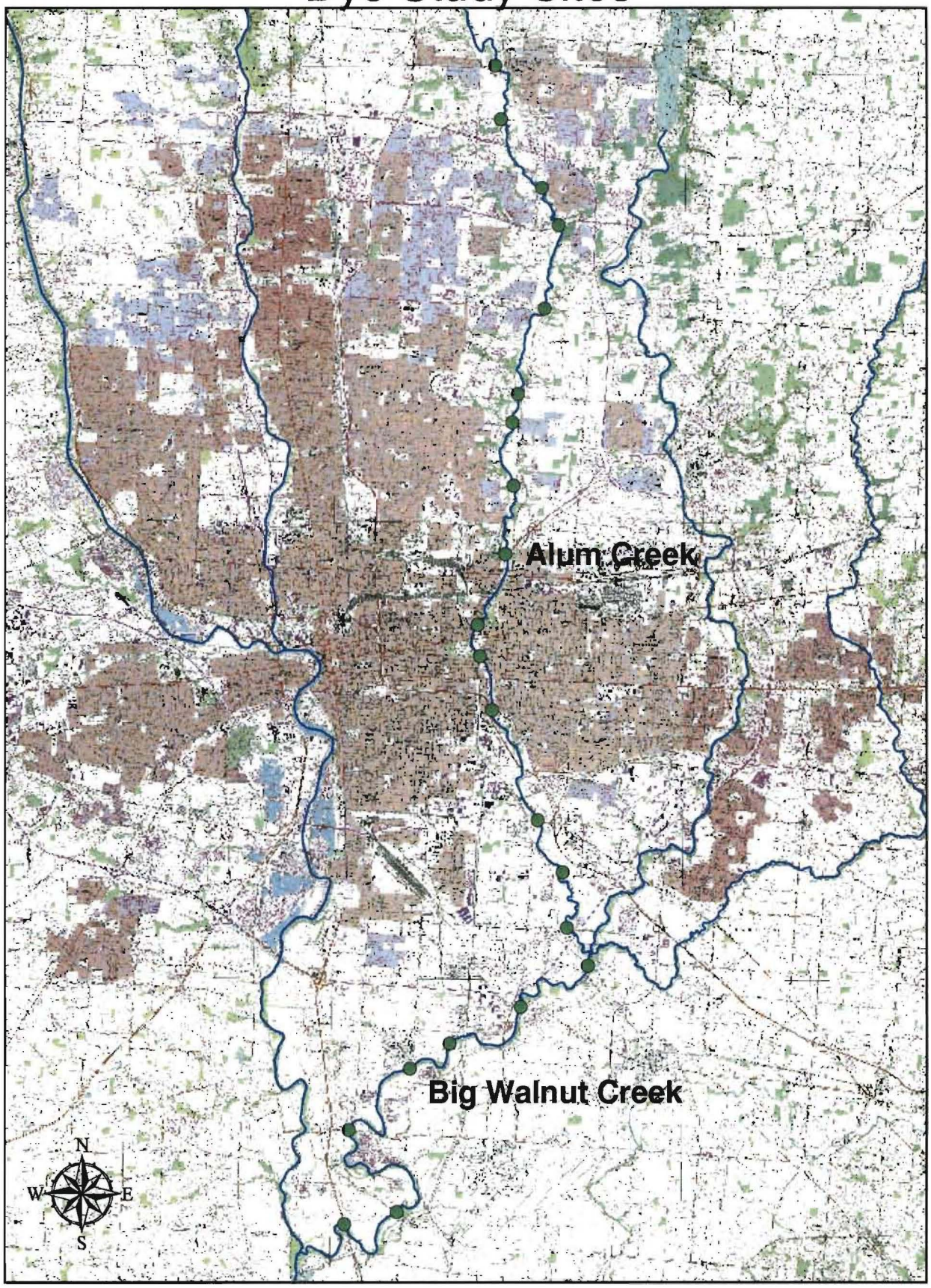
Appendix A

Site Location Map

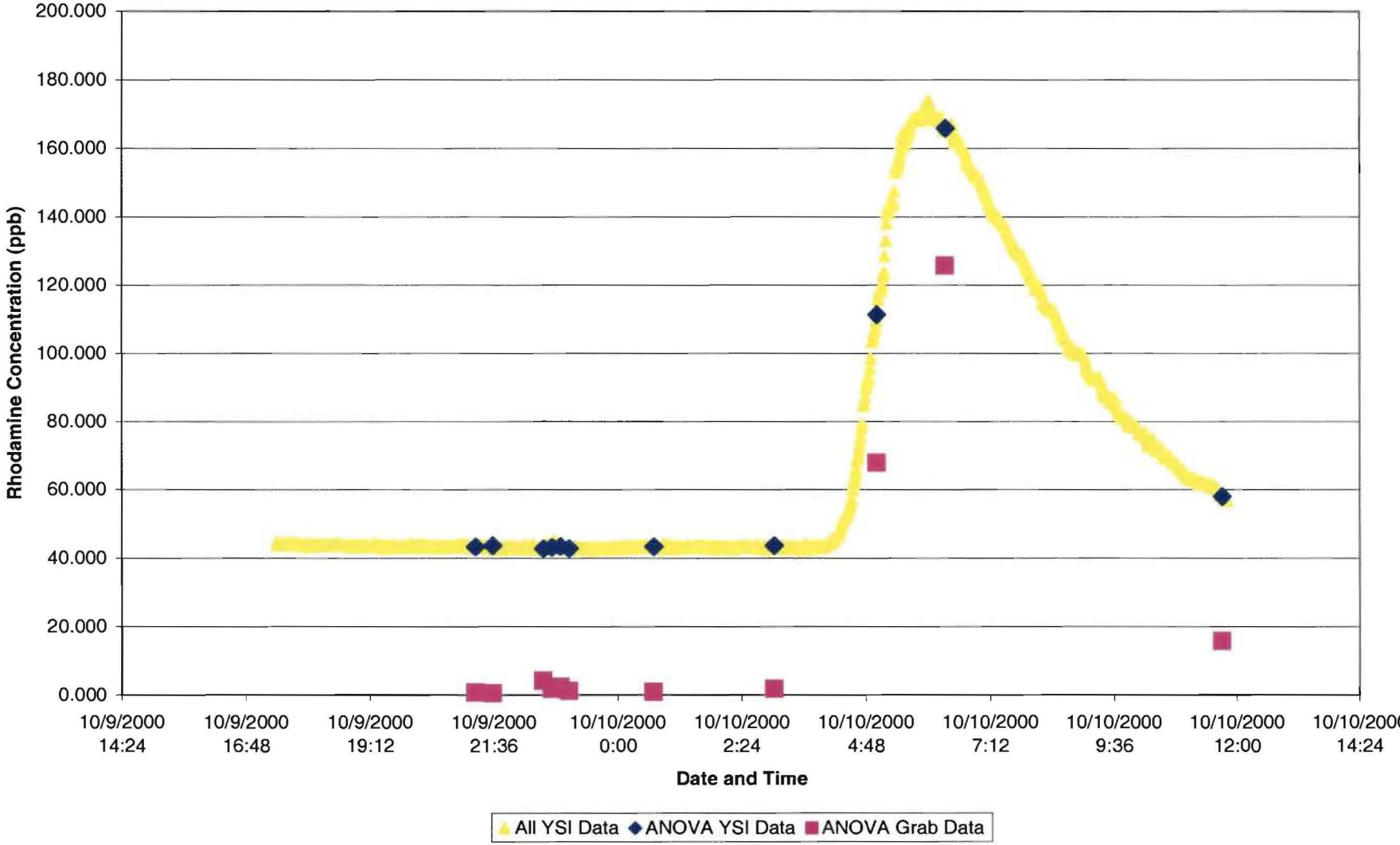
Appendix A
Big Walnut Creek and Alum Creek
Dye Study Sites



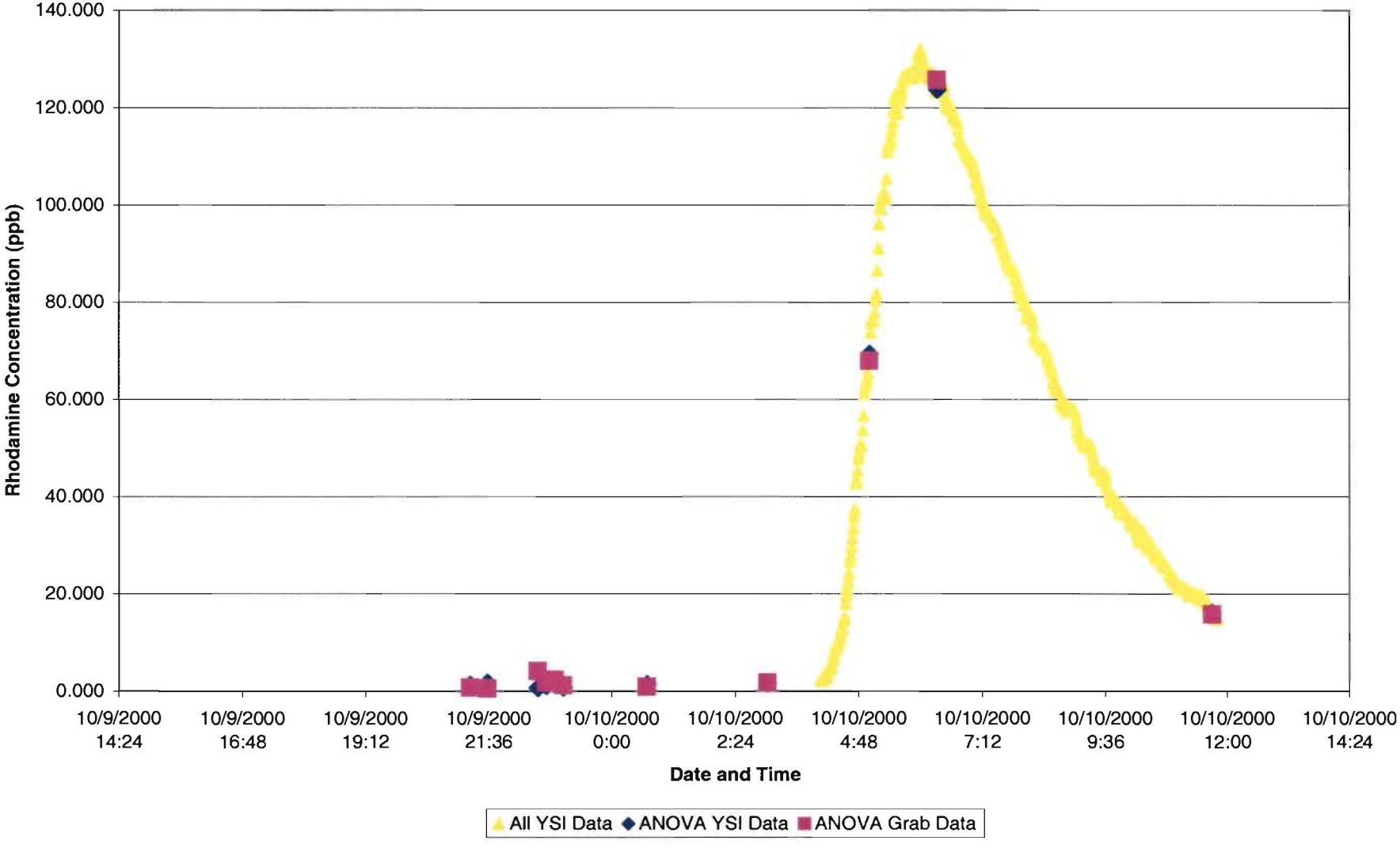
Appendix B

Dry Weather Data

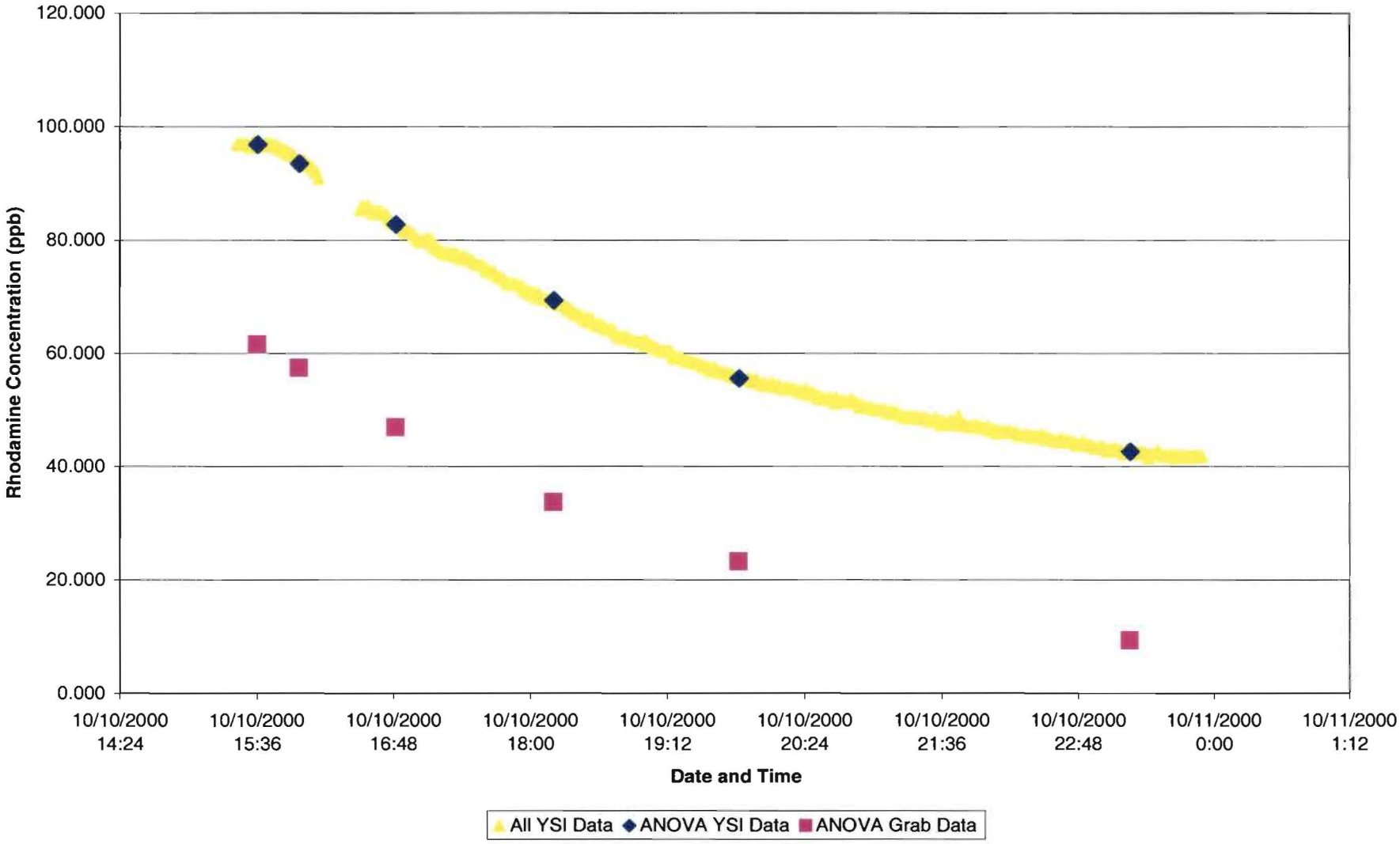
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Clifton Avenue (Injection at Airport Road)



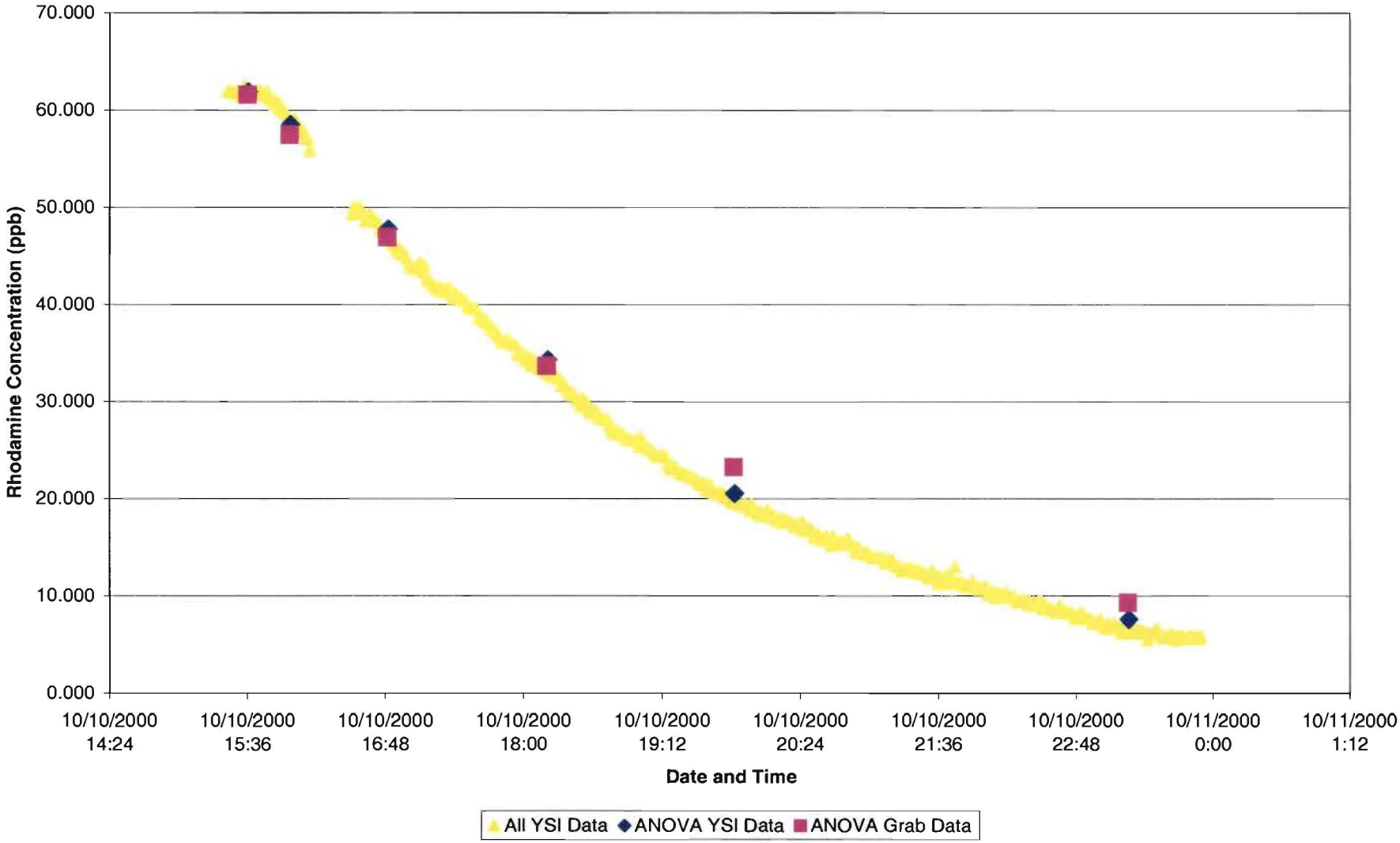
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Clifton Avenue (Injection at Airport Road)



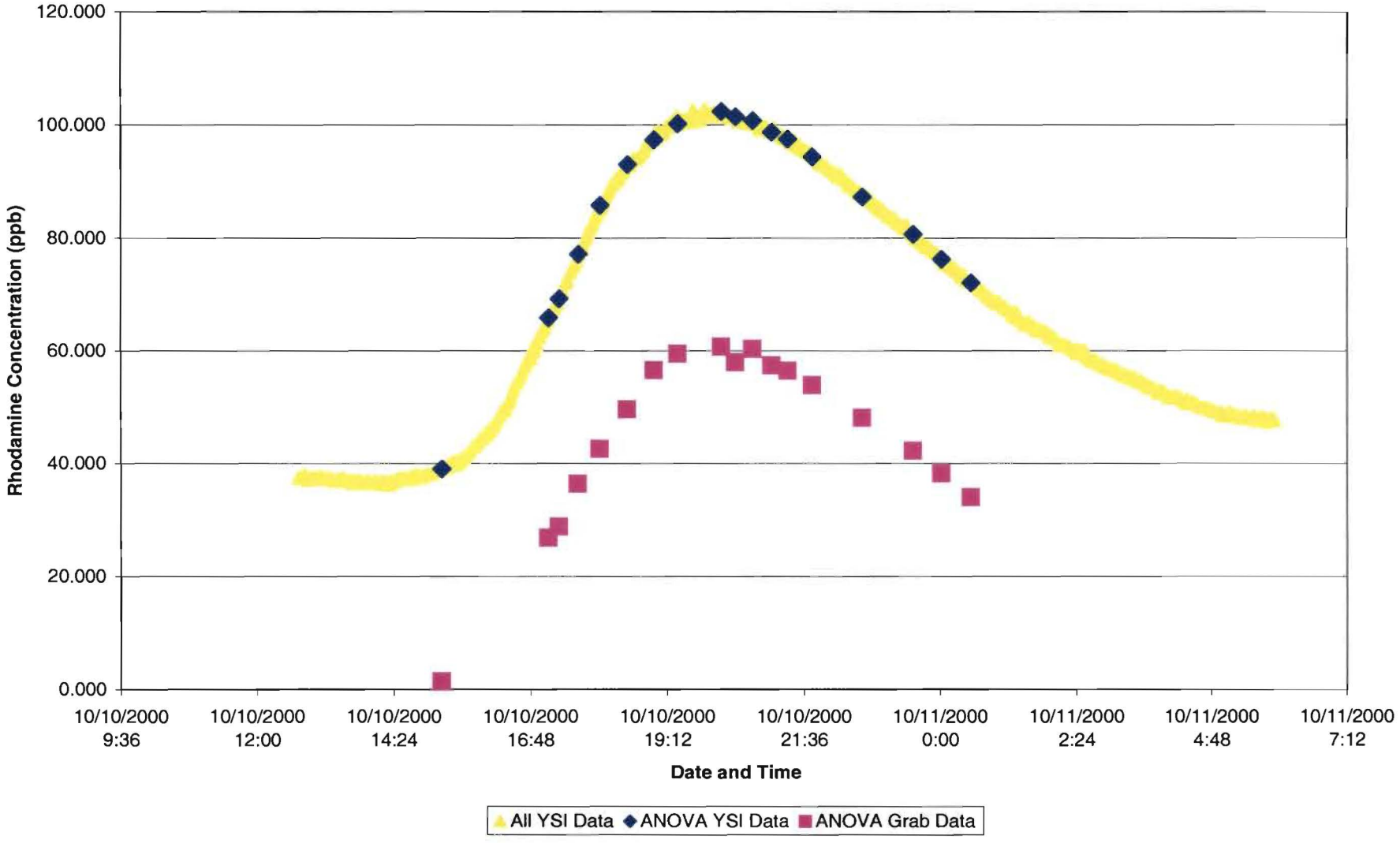
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Wolfe Park (Injection at Airport Road)



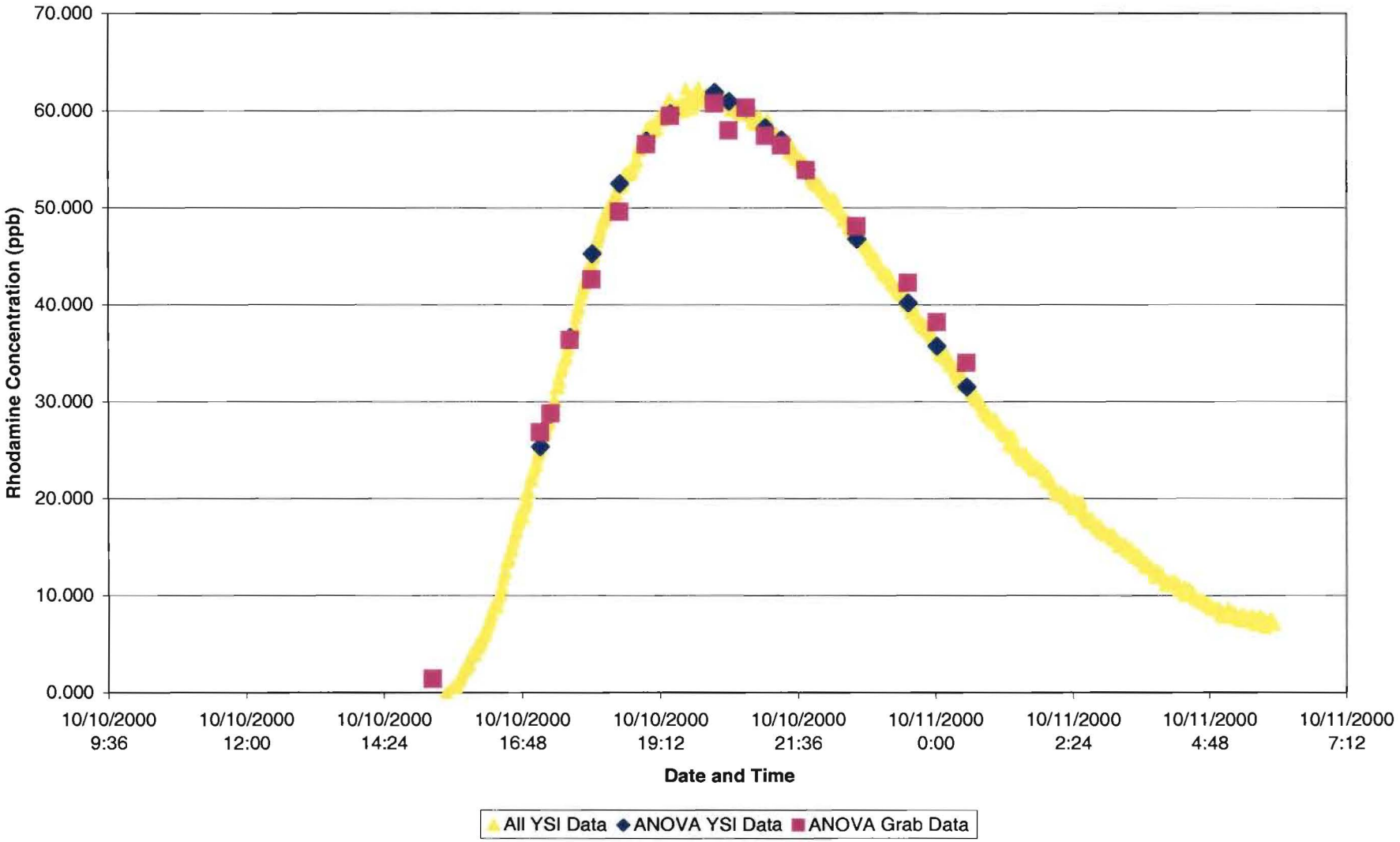
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Wolfe Park (Injection at Airport Road)



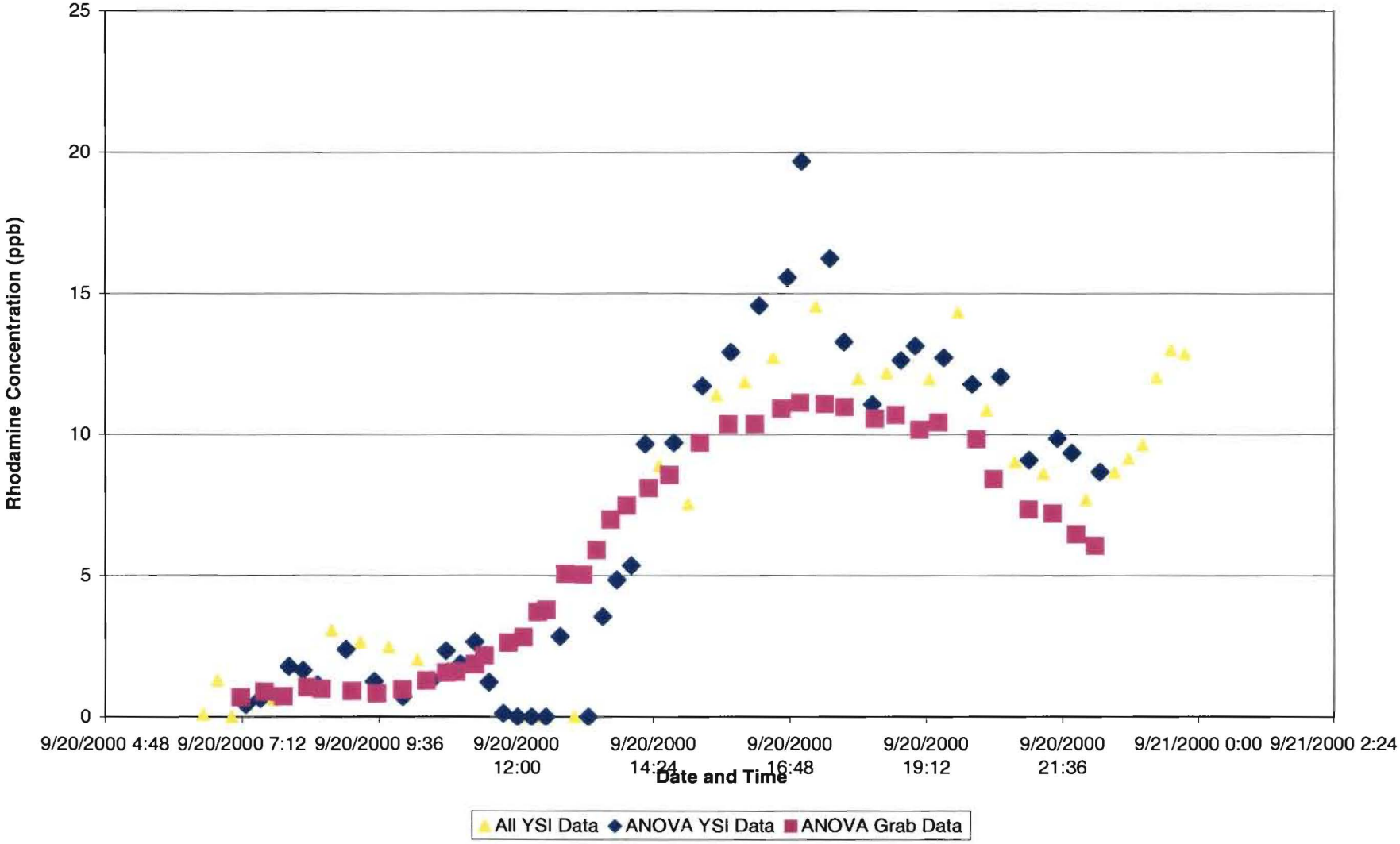
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Livingston Avenue (Injection at Airport Road)



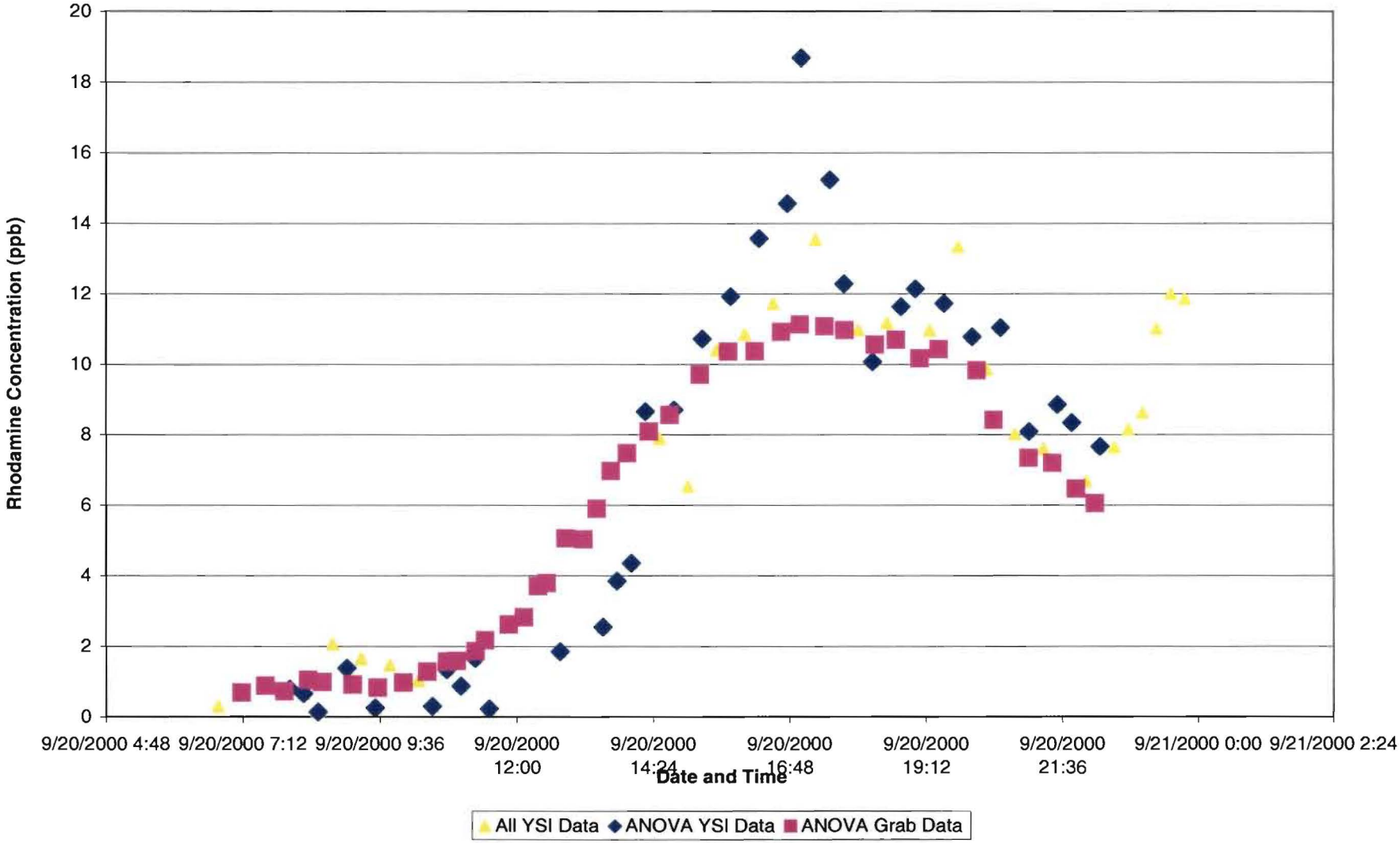
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Livingston Avenue (Injection at Airport Road)



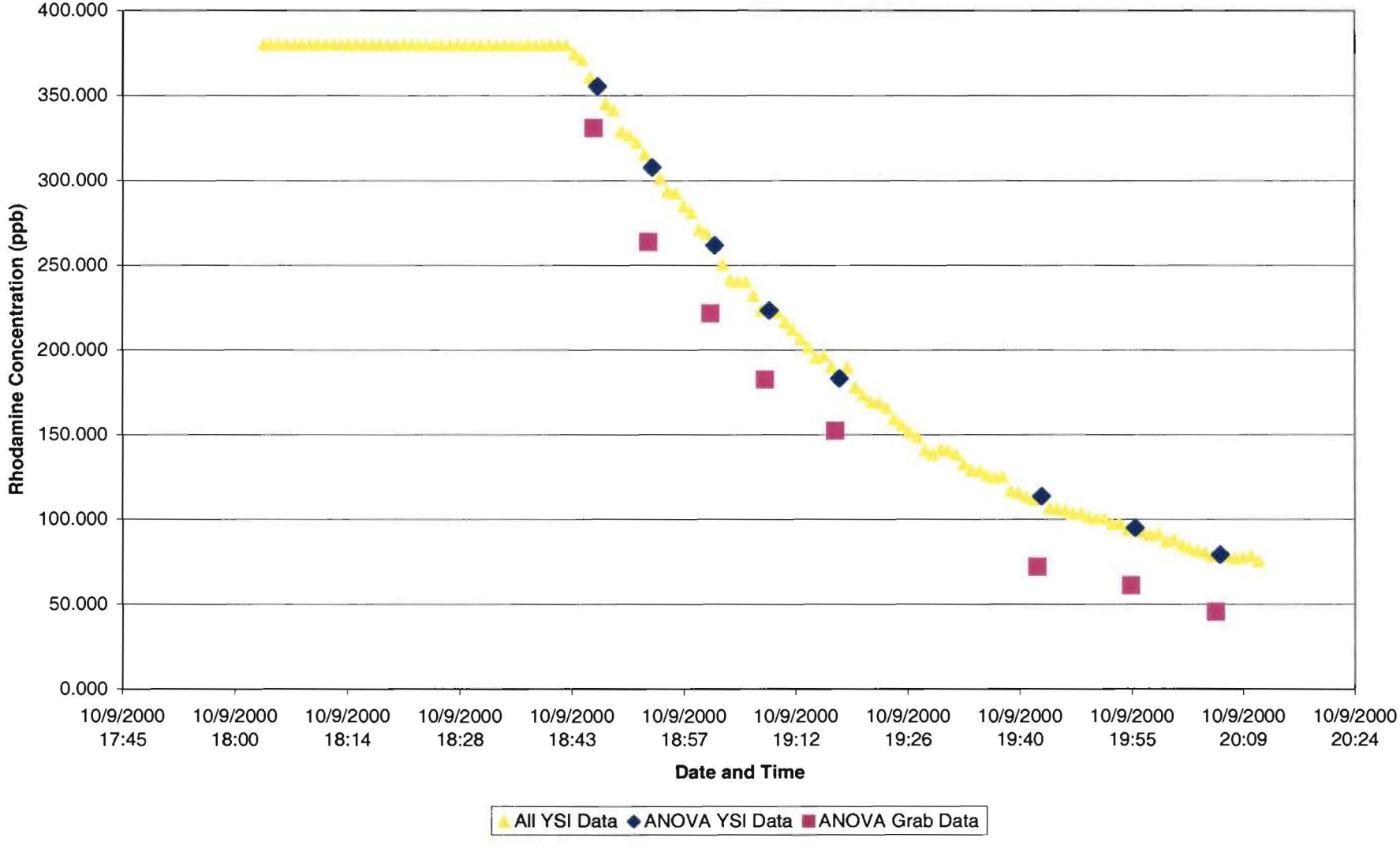
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Reese Road (Injection at 3-Rivers Footbridge)



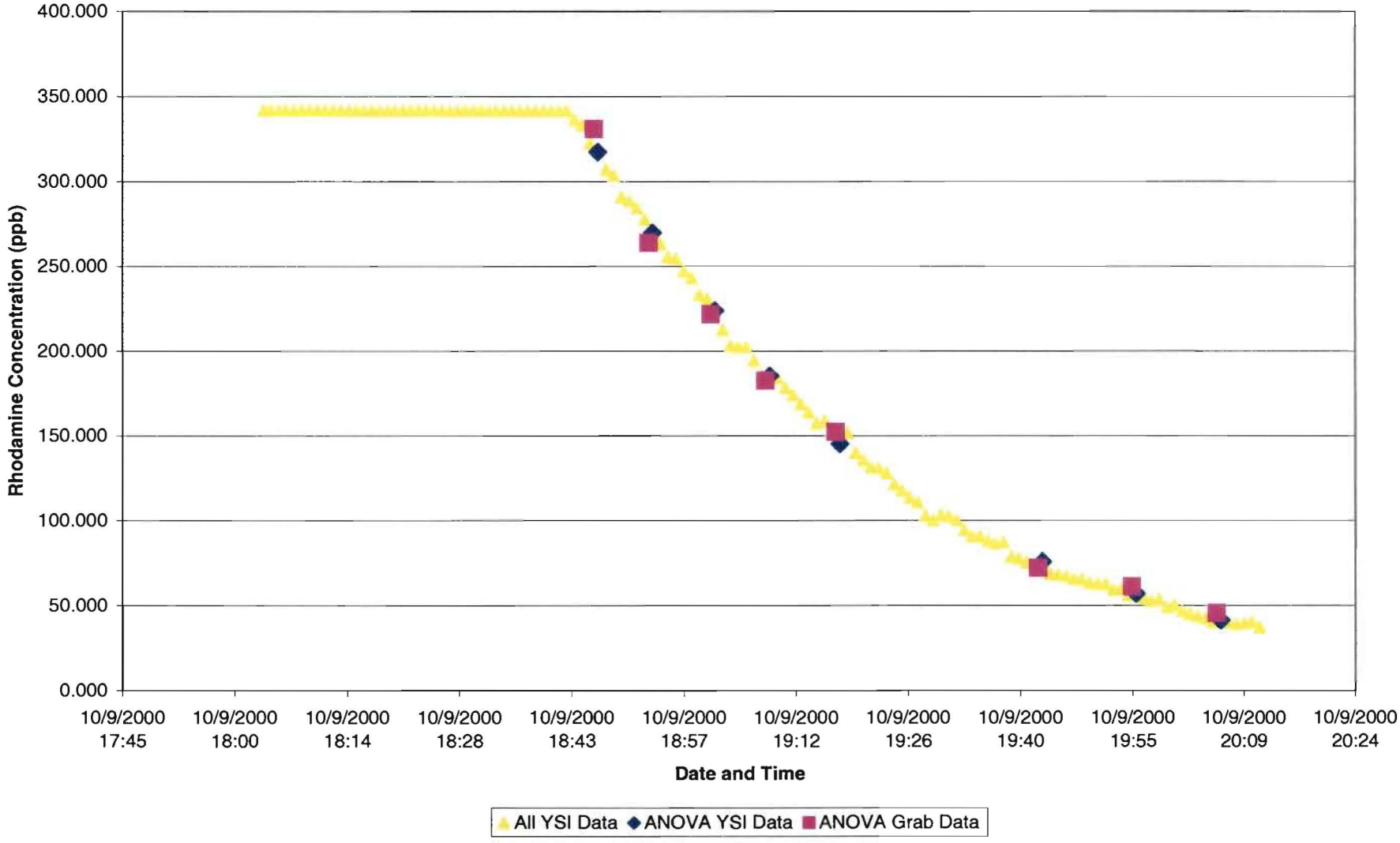
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Reese Road (Injection at 3-Rivers Footbridge)



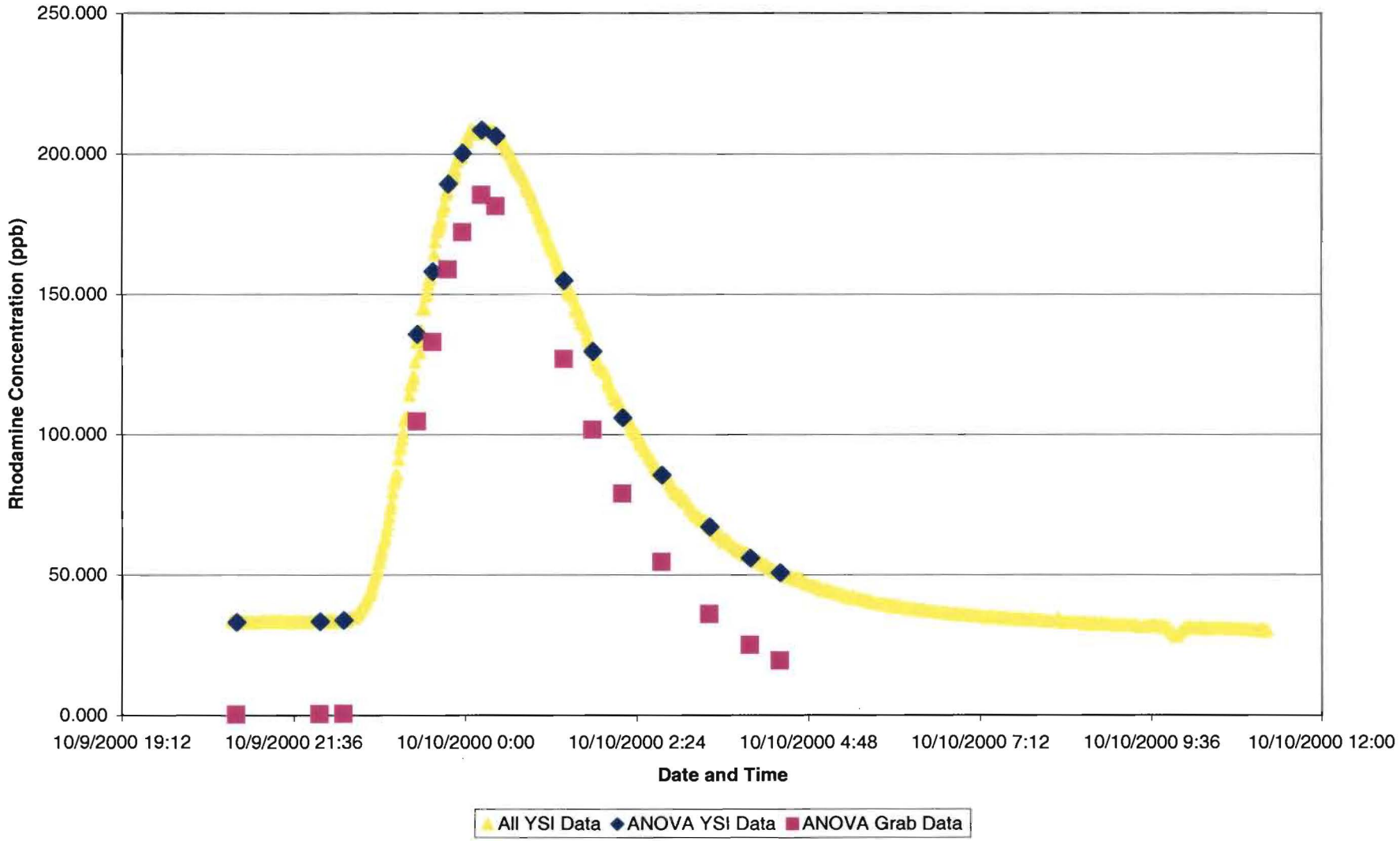
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Agler Road (Injection at Innis Road)



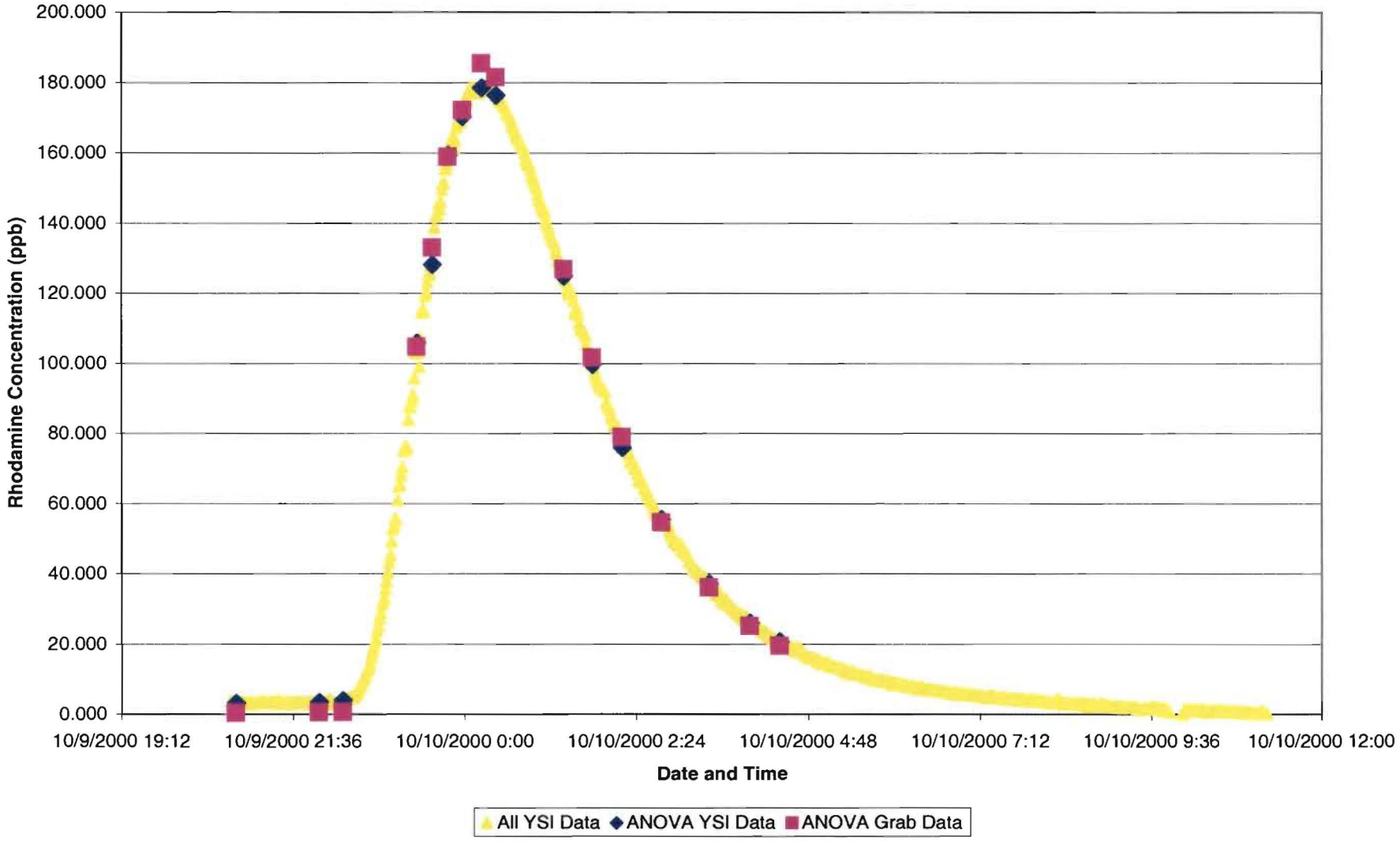
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Agler Road (Injection at Innis Road)



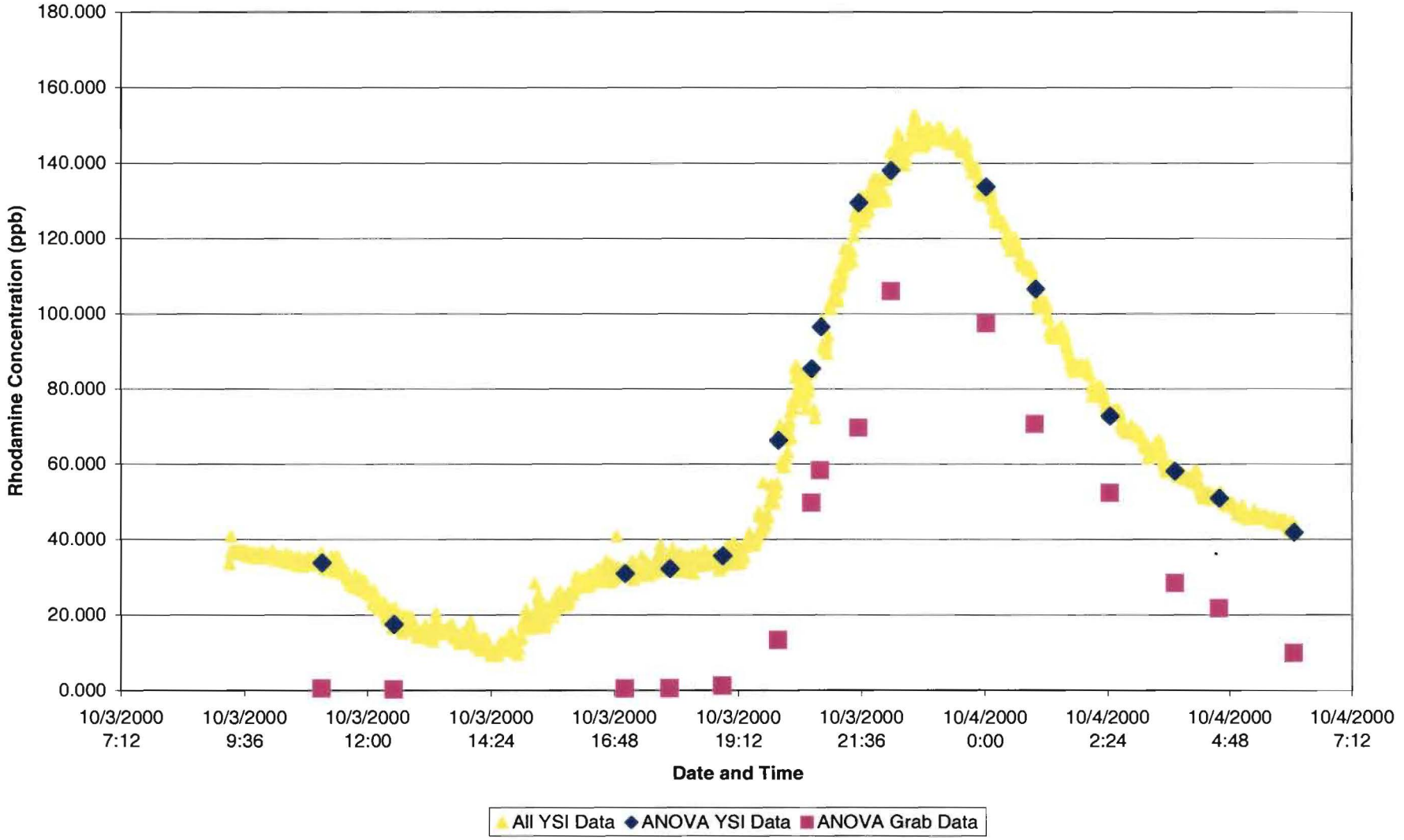
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Mock Road (Injection at Innis Road)



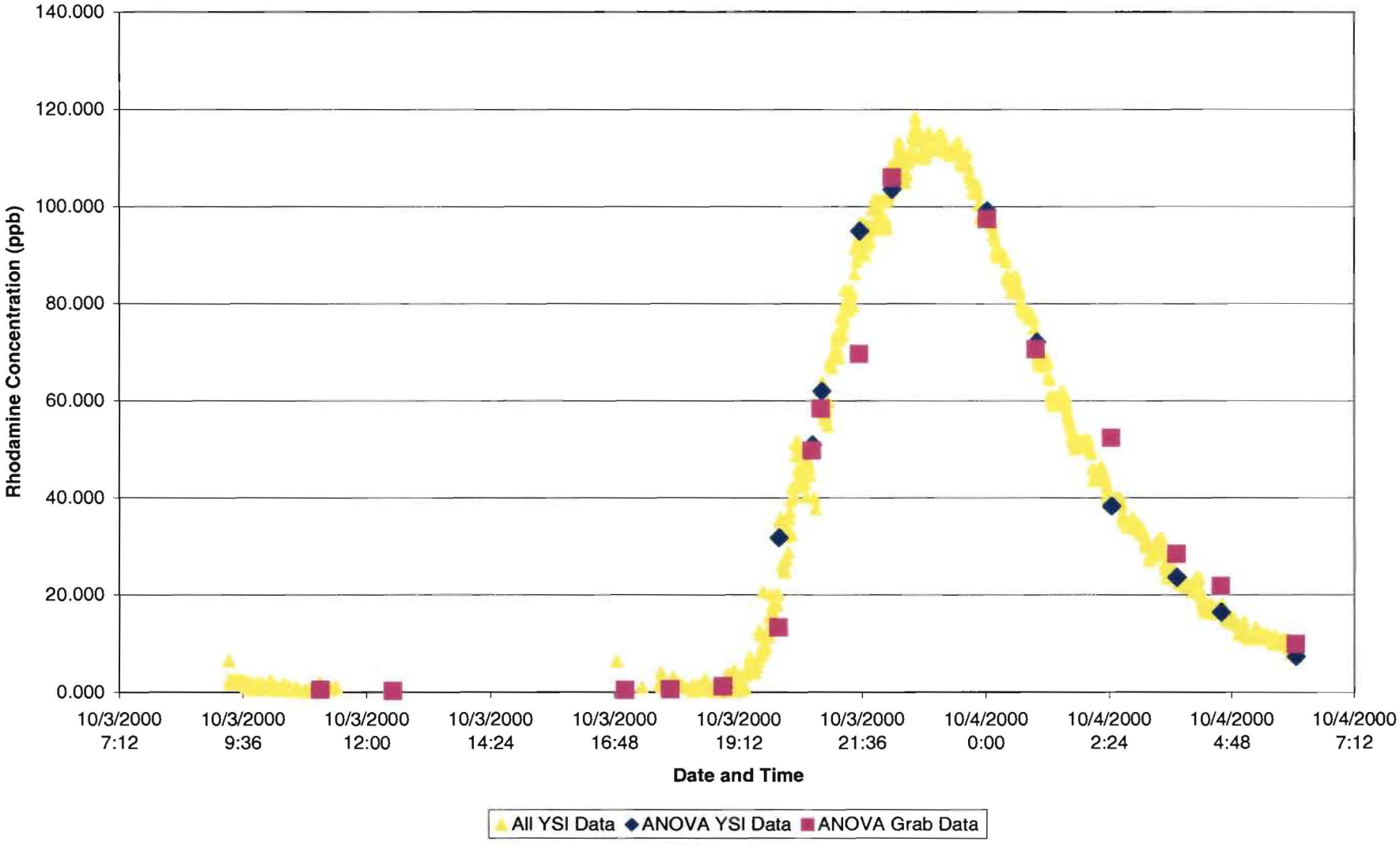
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Mock Road (Injection at Innis Road)



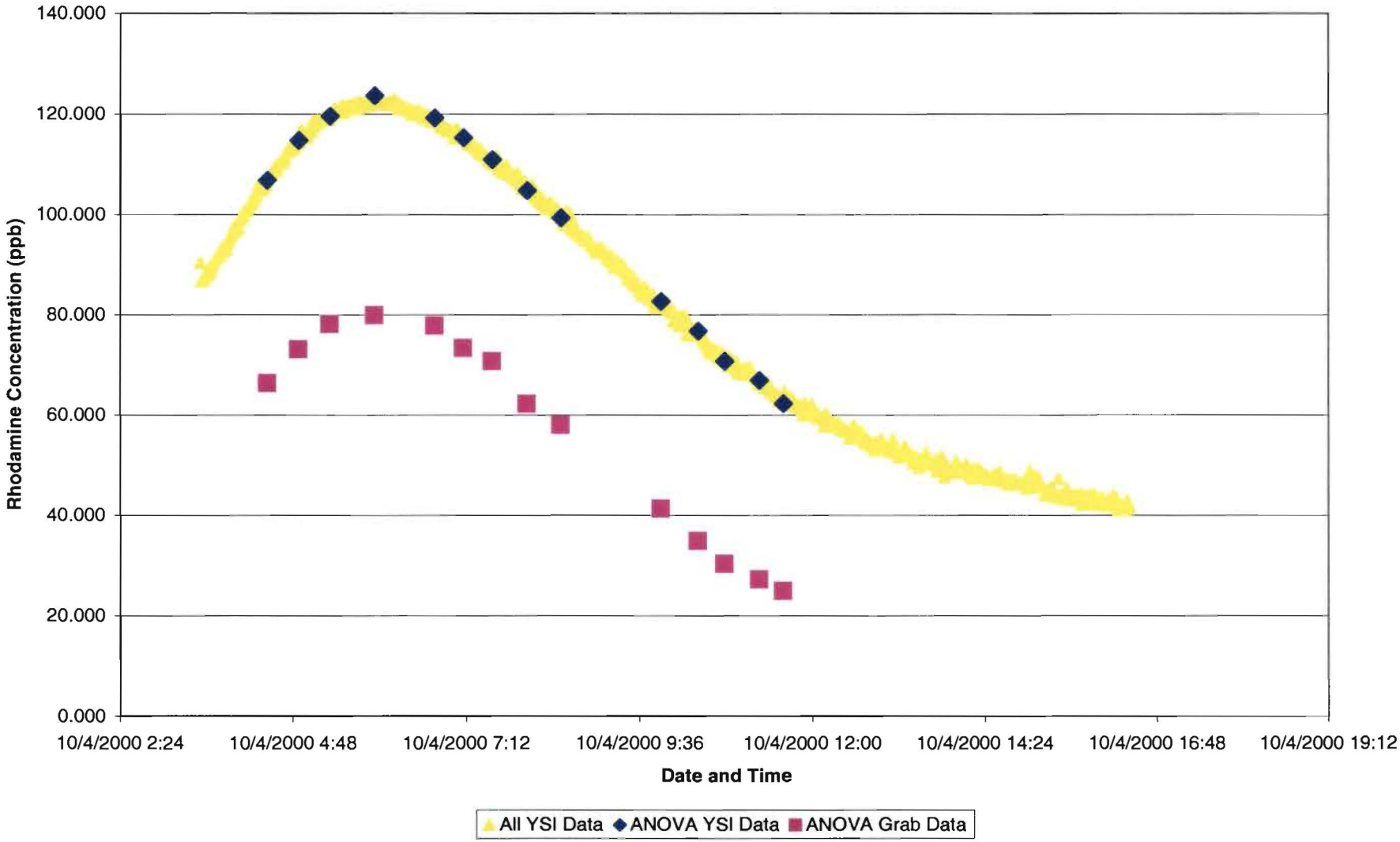
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at S.R. 104 (Injection at Livingston Avenue)



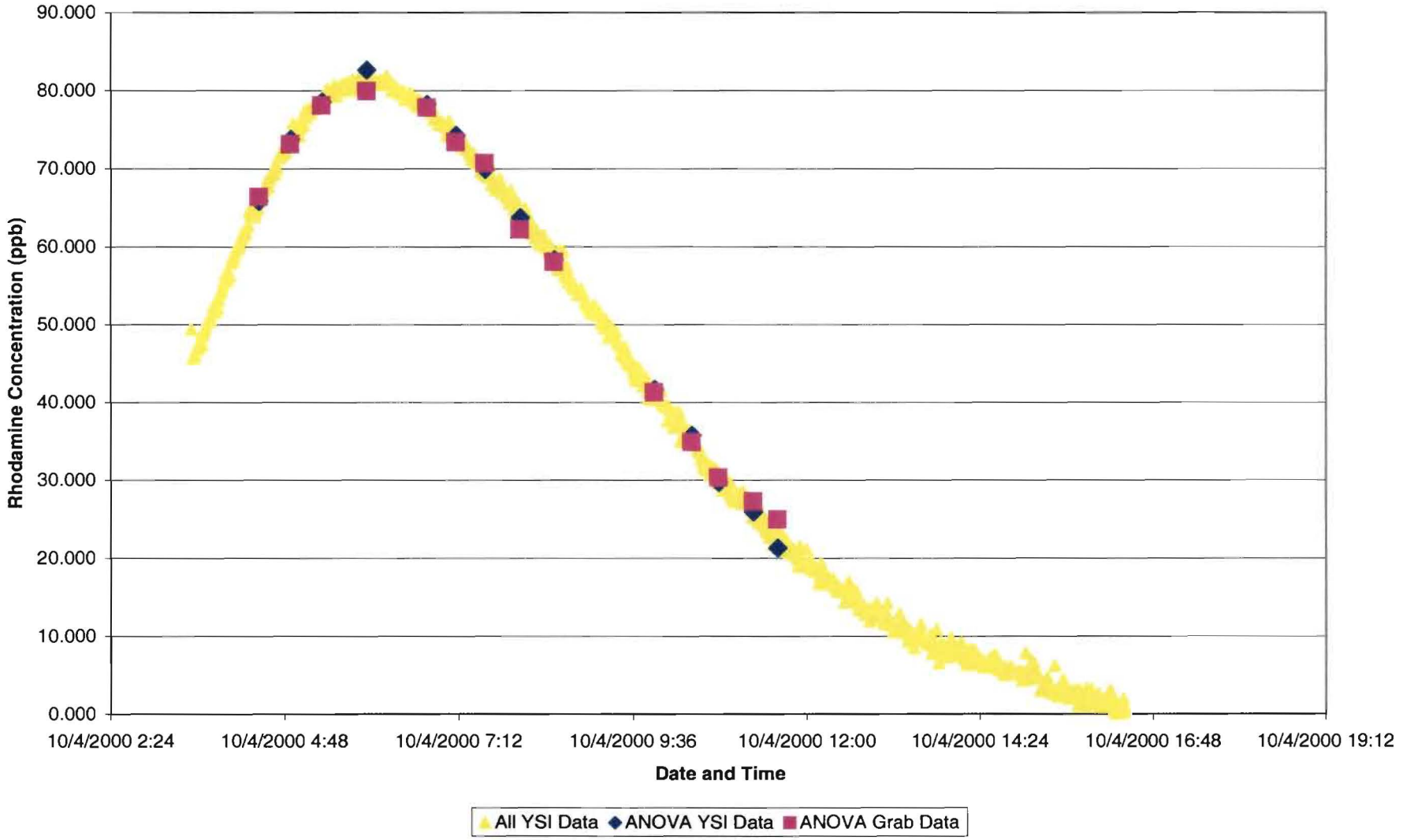
Appendix B Dry Weather Data
Post-Background Subtraction Curve at S.R. 104 (Injection at Livingston Avenue)



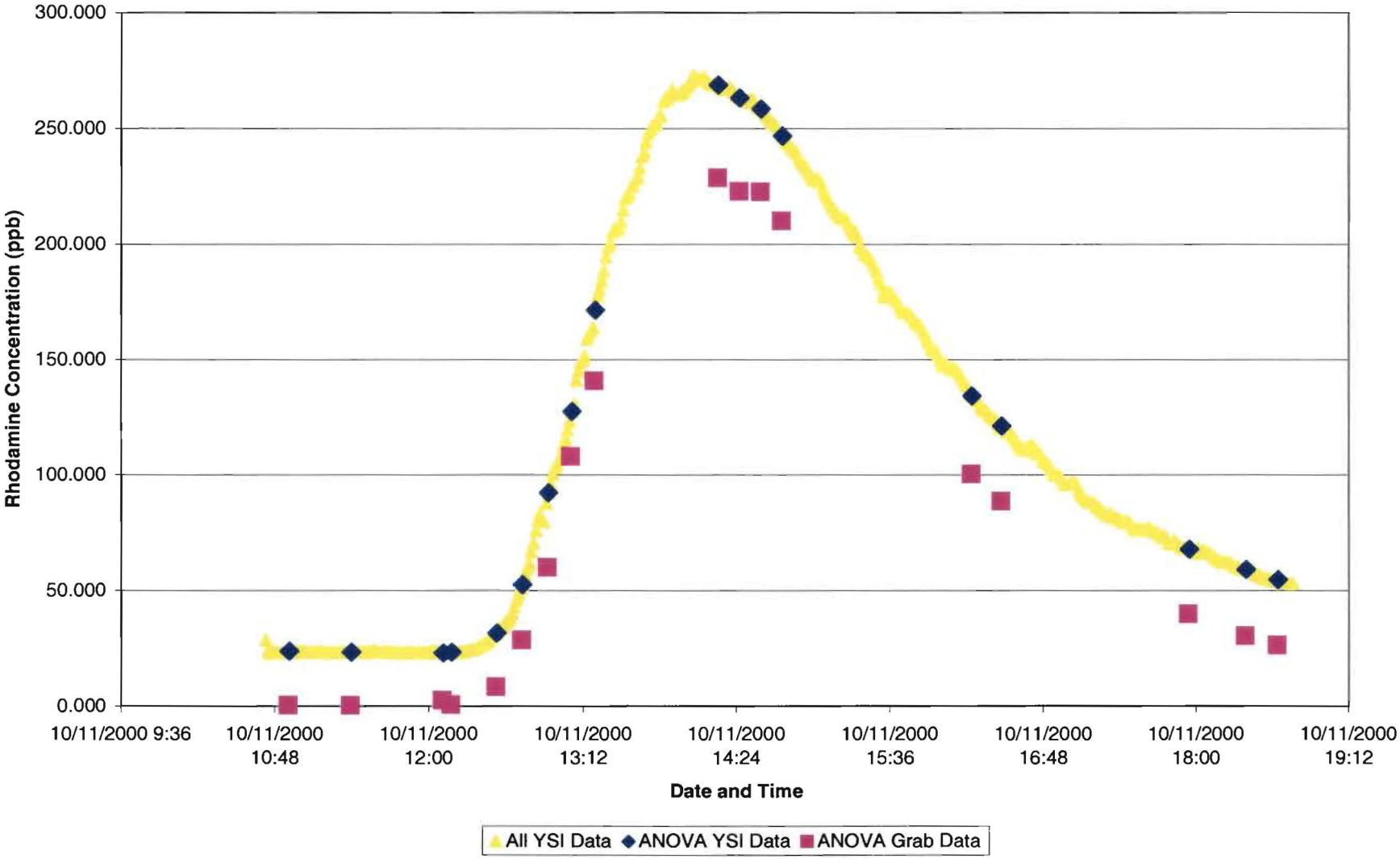
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Watkins Road (Injection at Livingston Avenue)



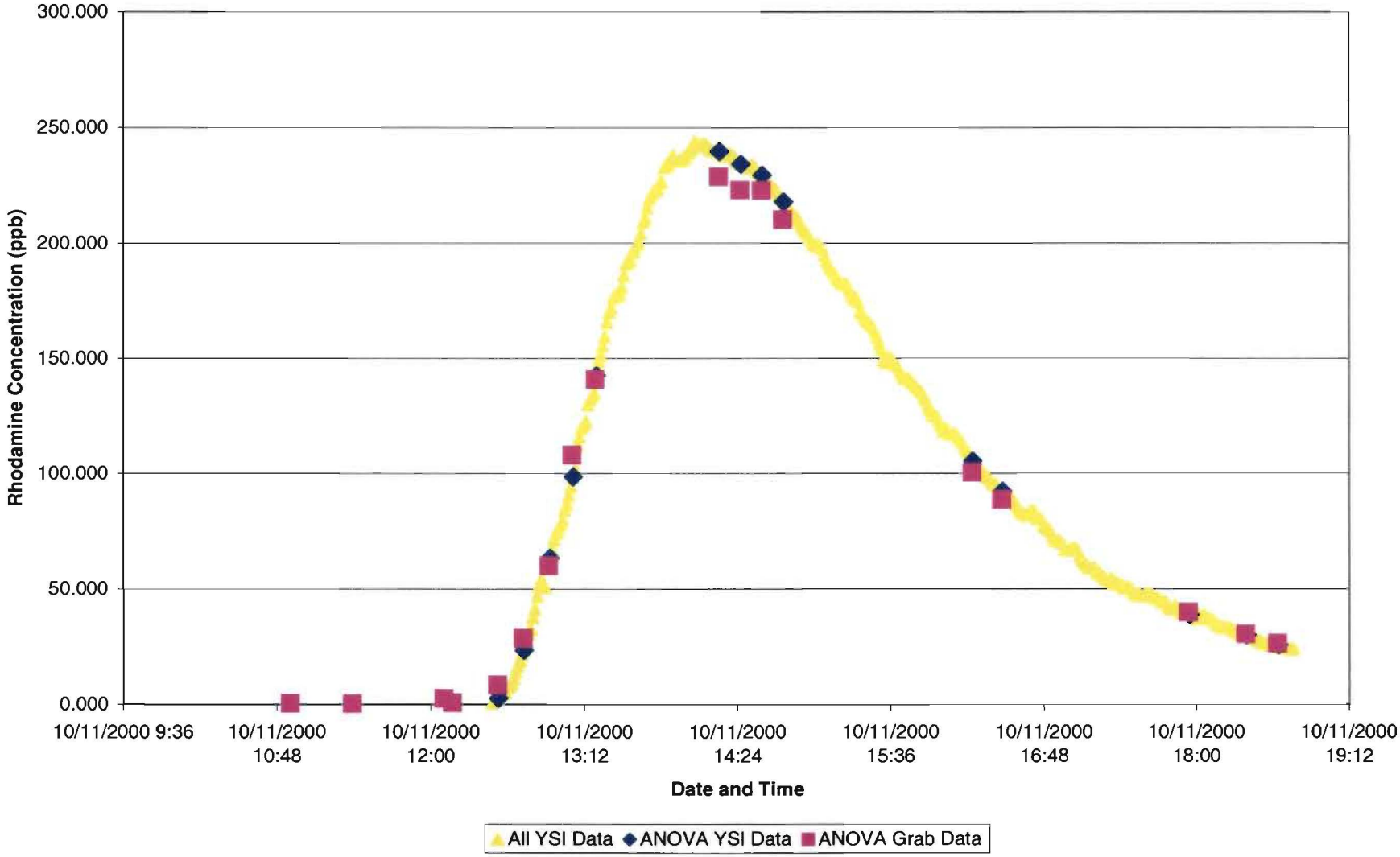
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Watkins Road (Injection at Livingston Avenue)



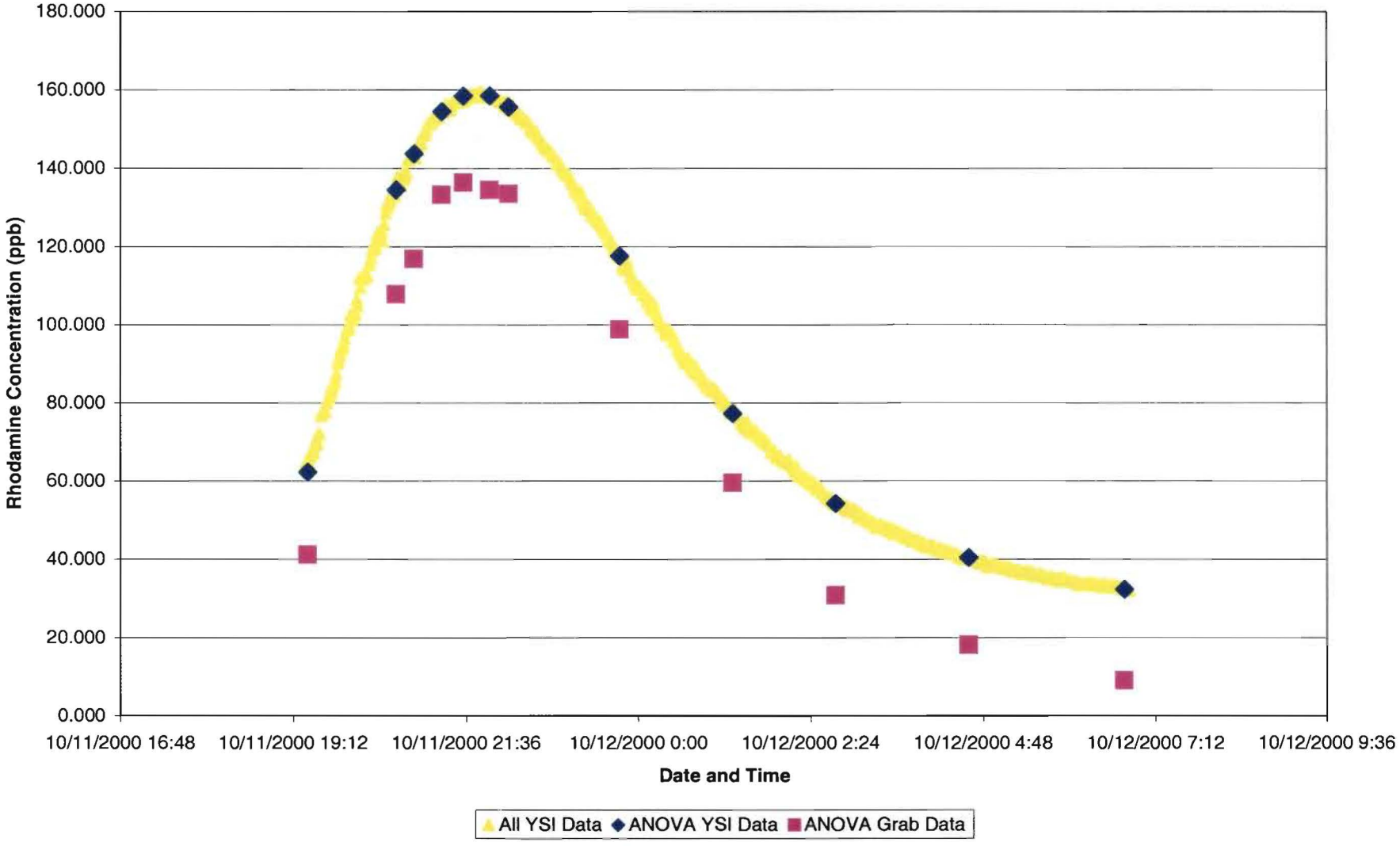
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Schrock Road (Injection at Main Street-Westerville)



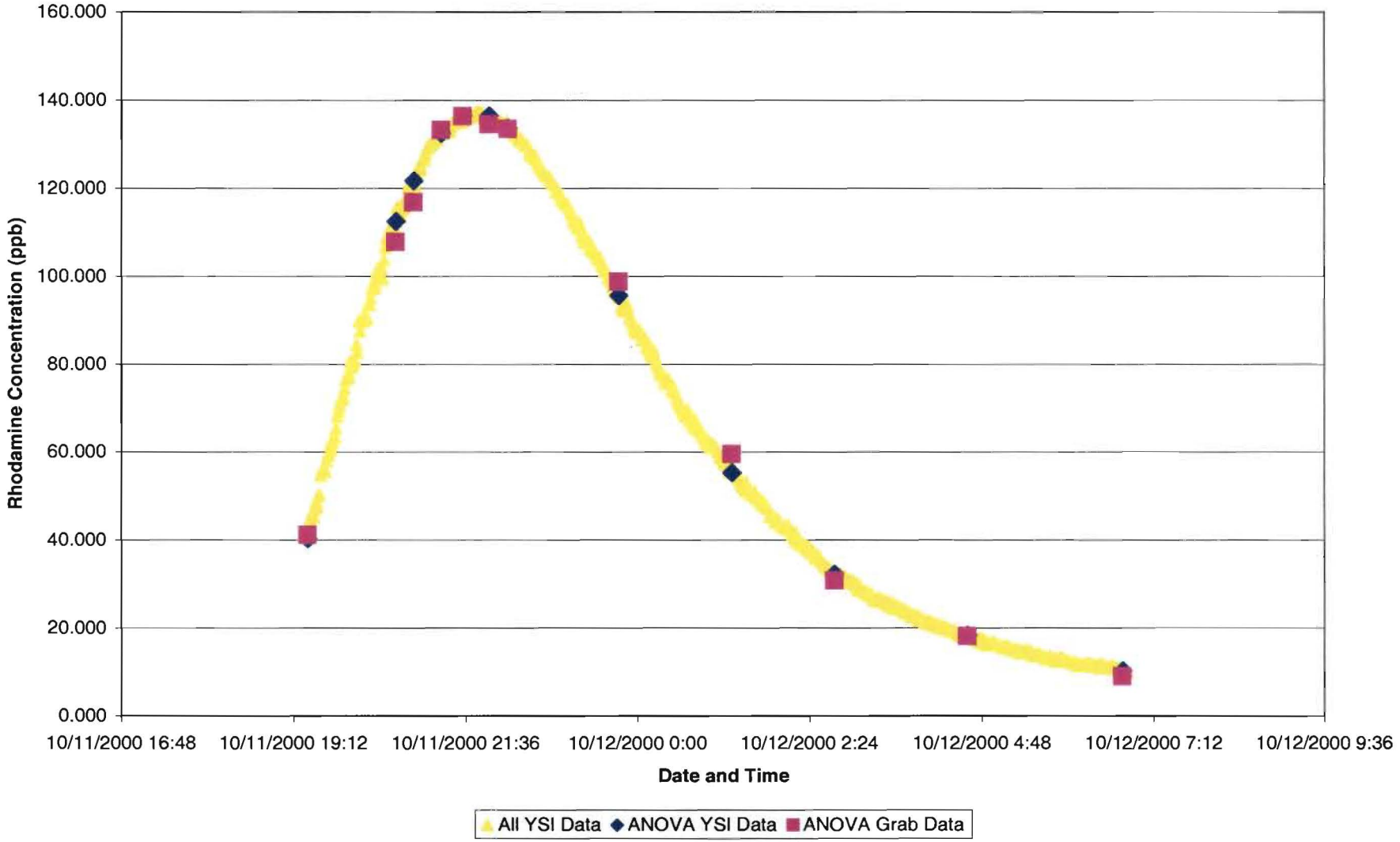
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Schrock Road (Injection at Main Street-Westerville)



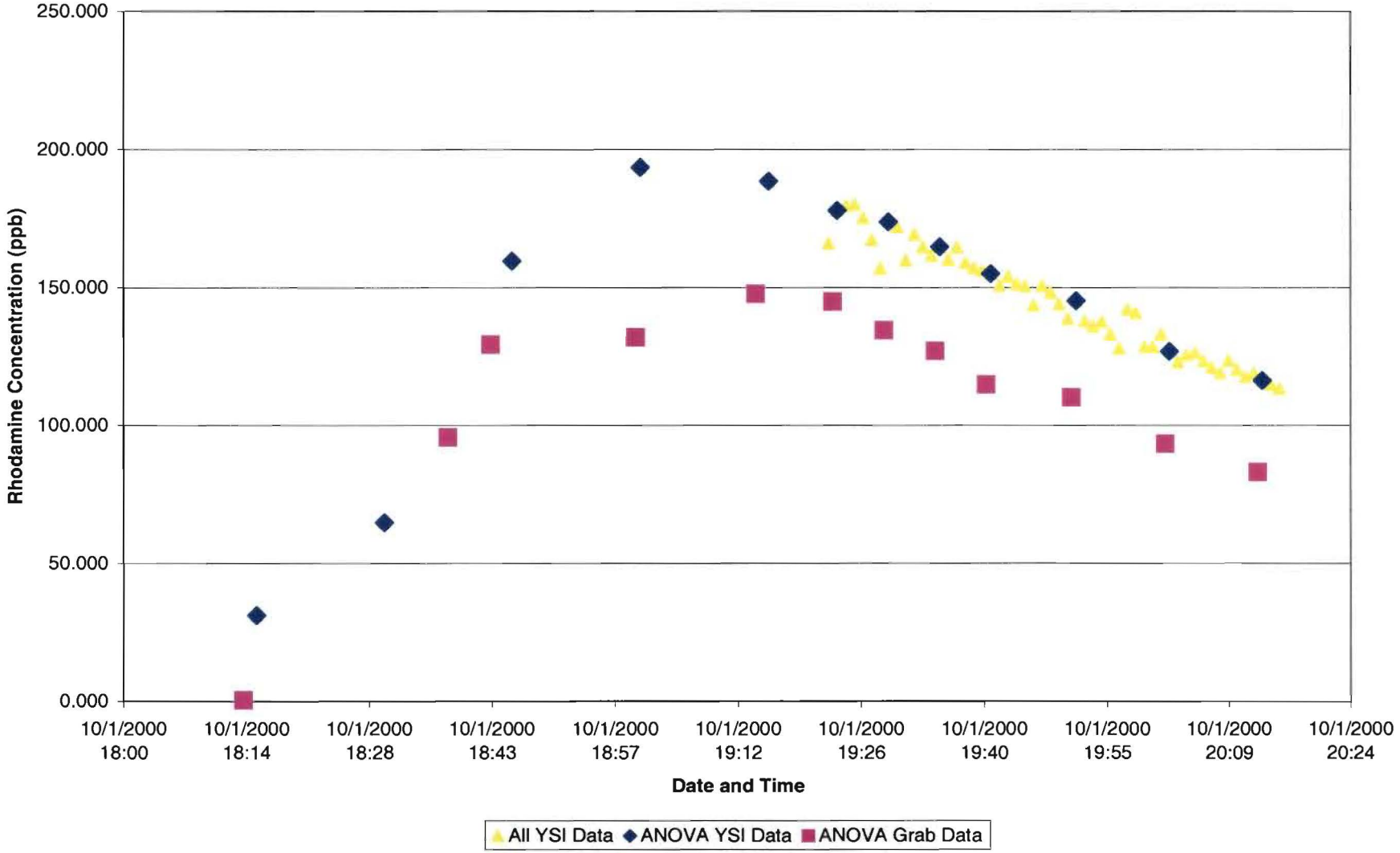
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Route 3 (Injection at Main Street-Westerville)



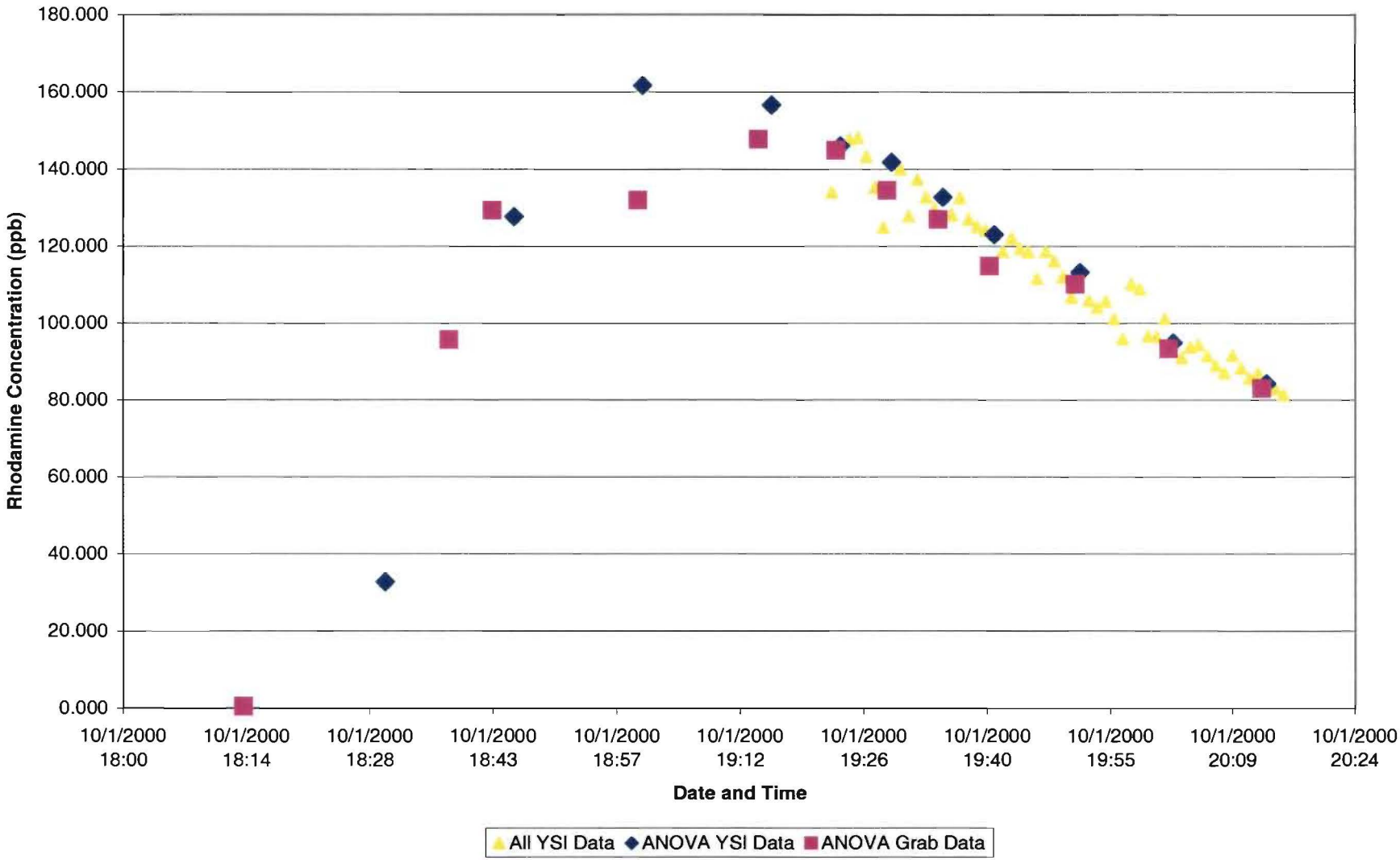
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Route 3 (Injection at Main Street-Westerville)



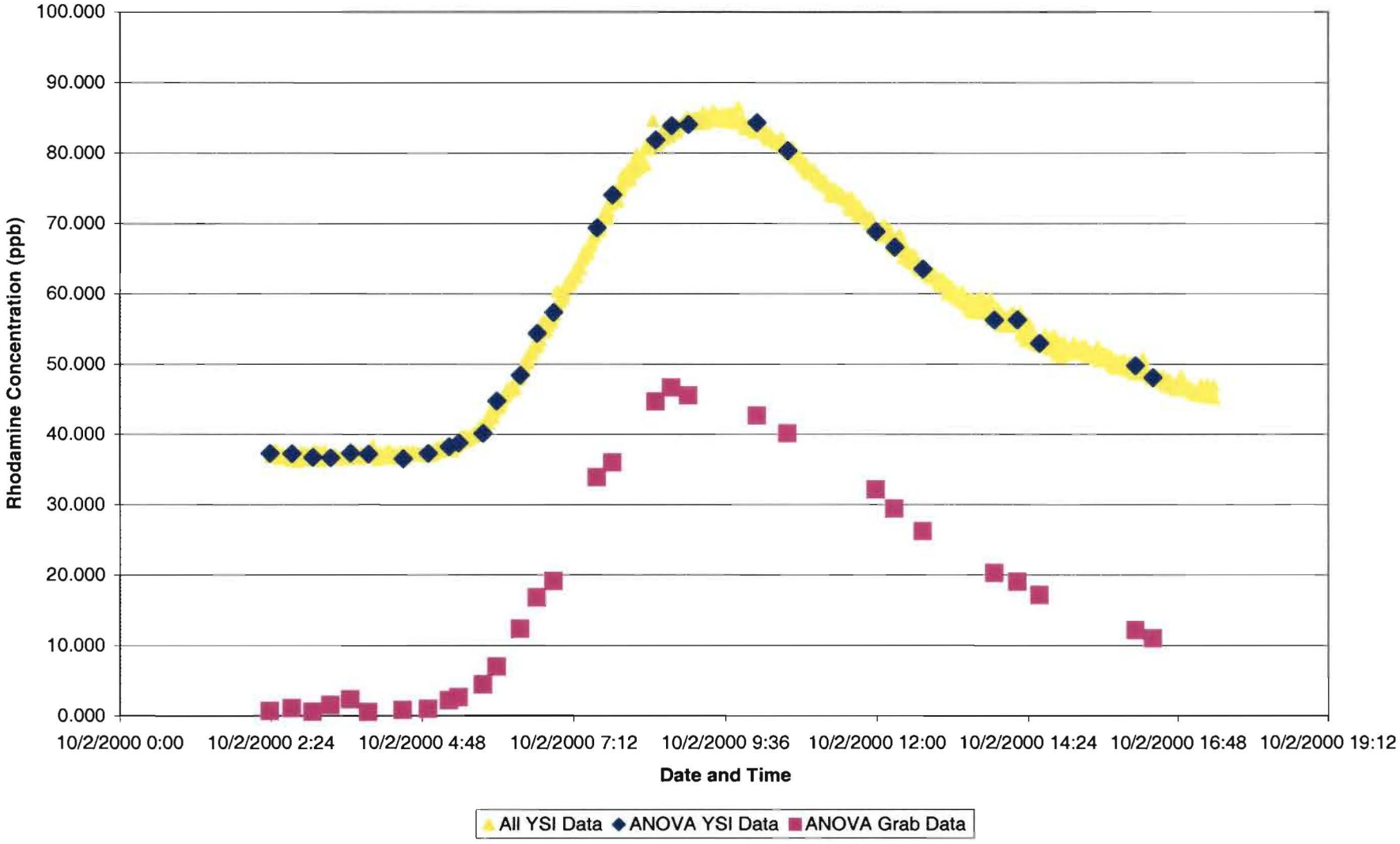
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Lockborne Road (Injection at Reese Road)



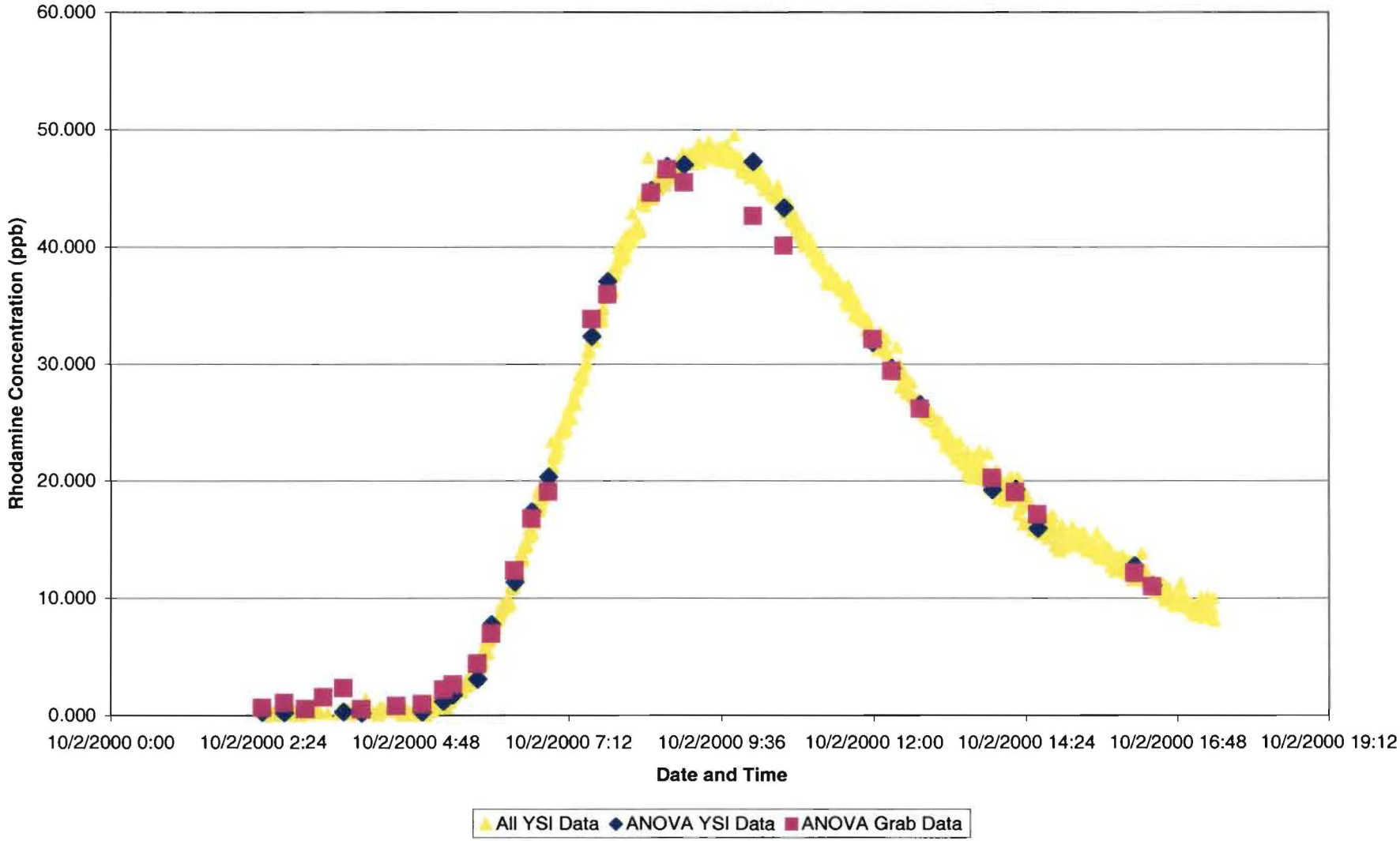
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Lockborne Road (Injection at Reese Road)



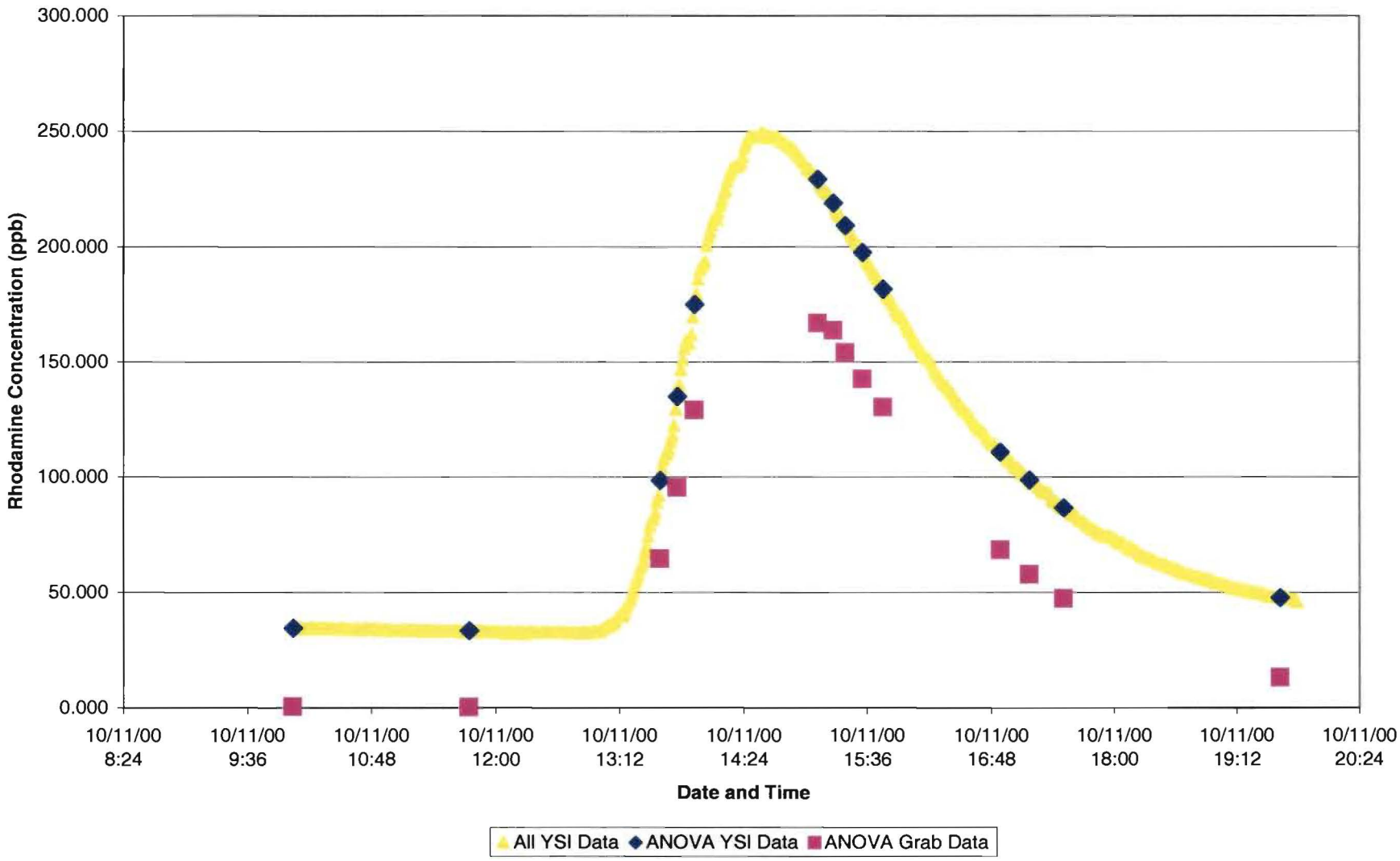
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at S.R. 317 (Injection at Reese Road)



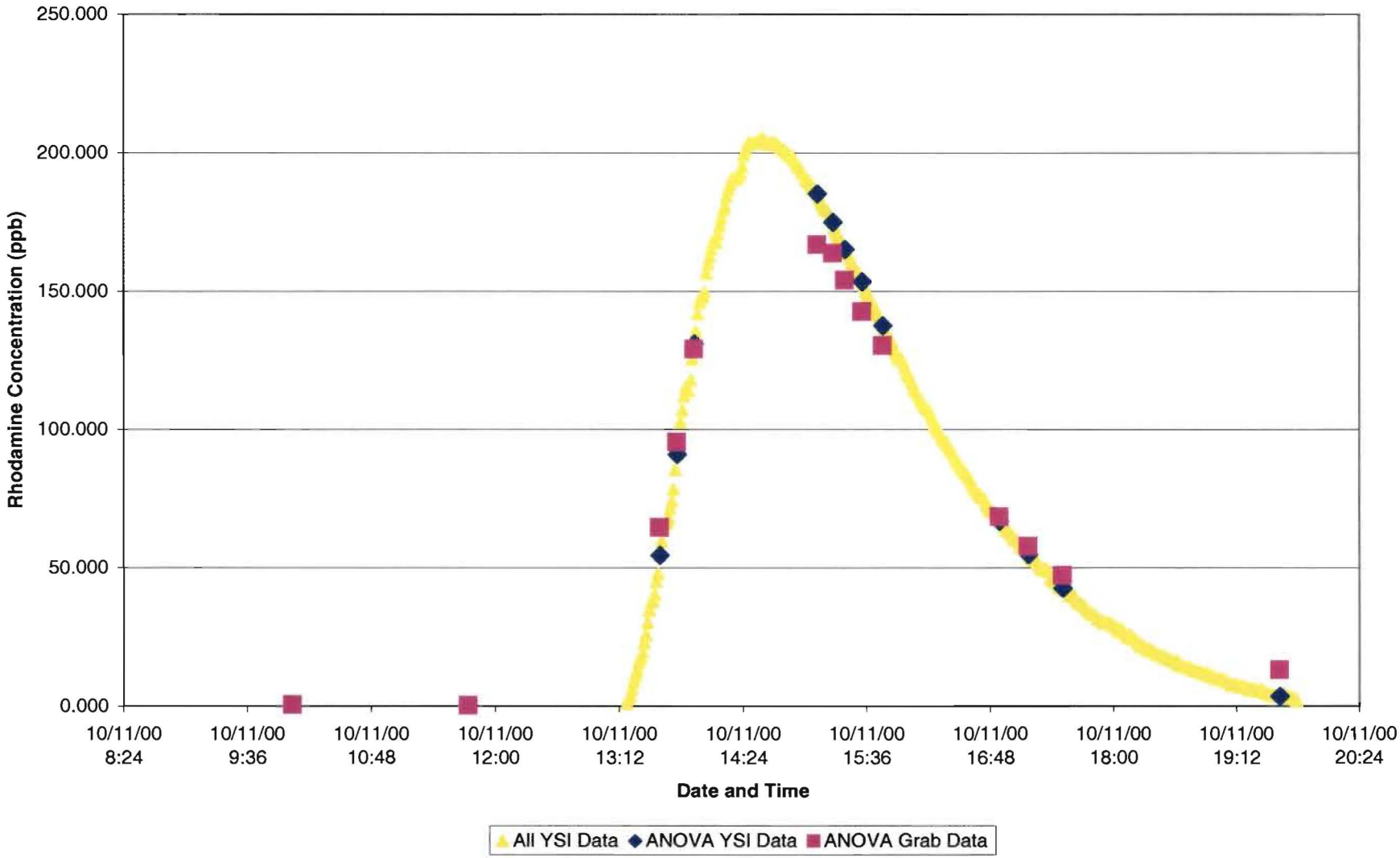
Appendix B Dry Weather Data
Post-Background Subtraction Curve at S.R. 317 (Injection at Reese Road)



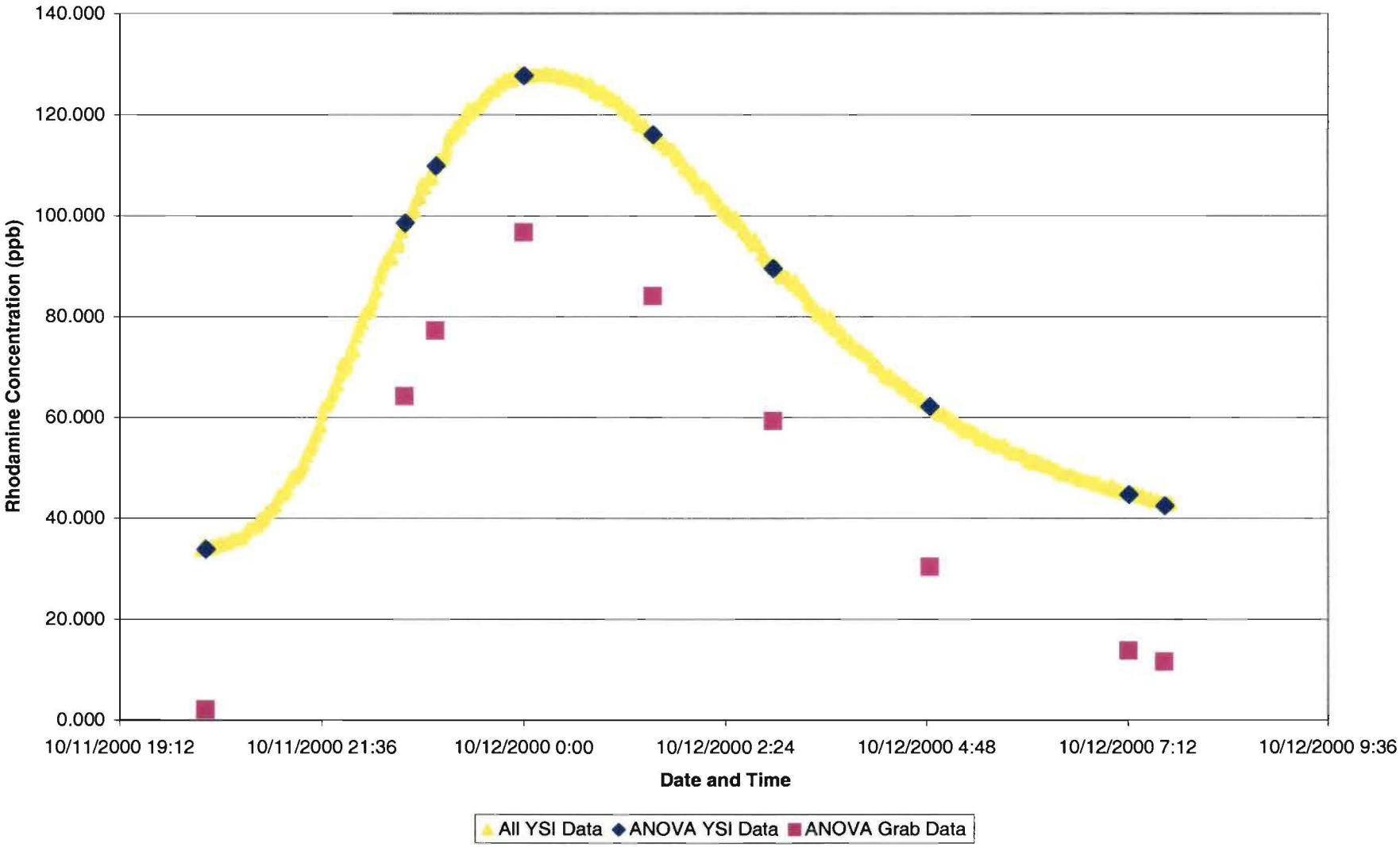
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Morse Road (Injection at S.R. 161)



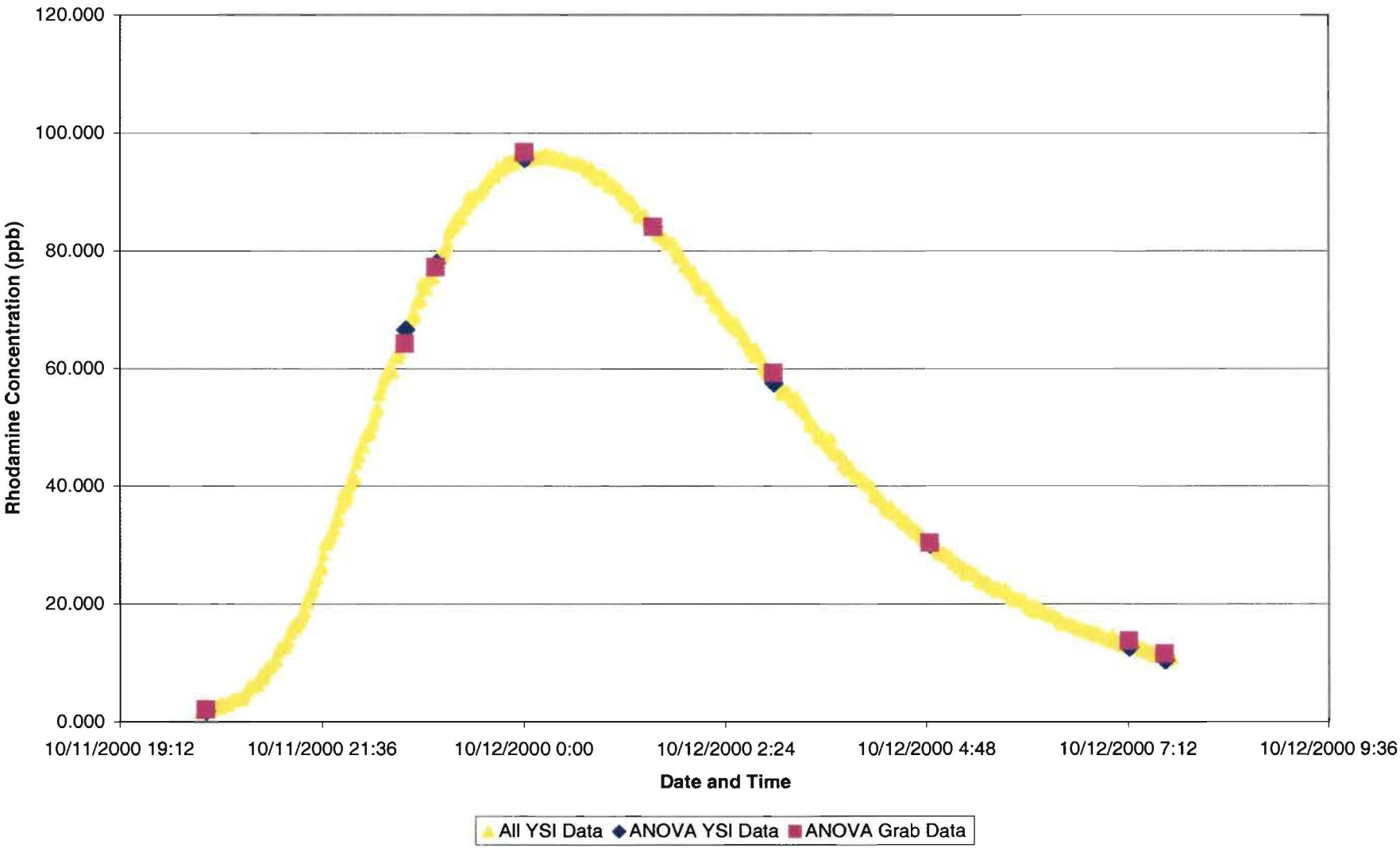
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Morse Road (Injection at S.R. 161)



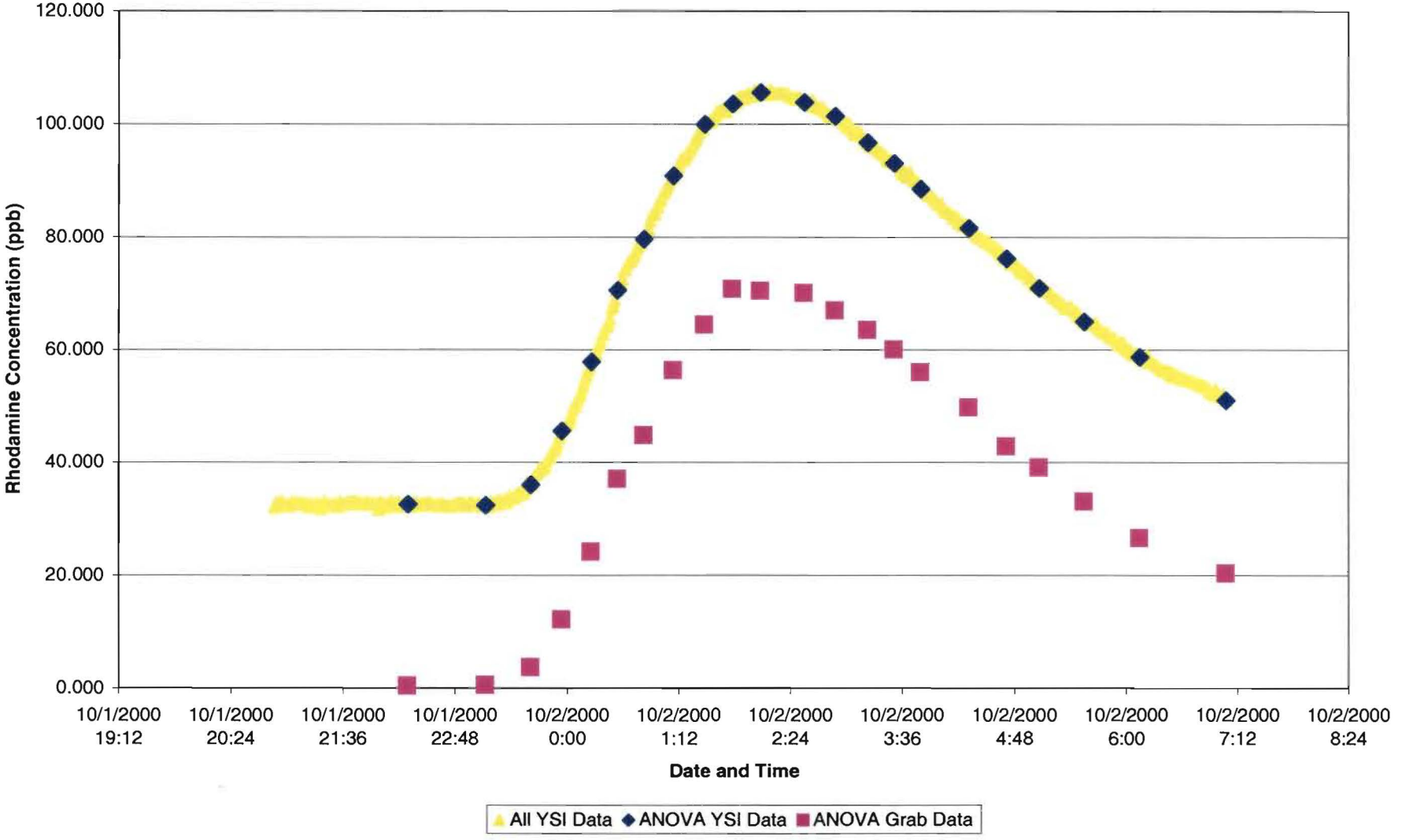
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Innis Road (Injection at S.R. 161)



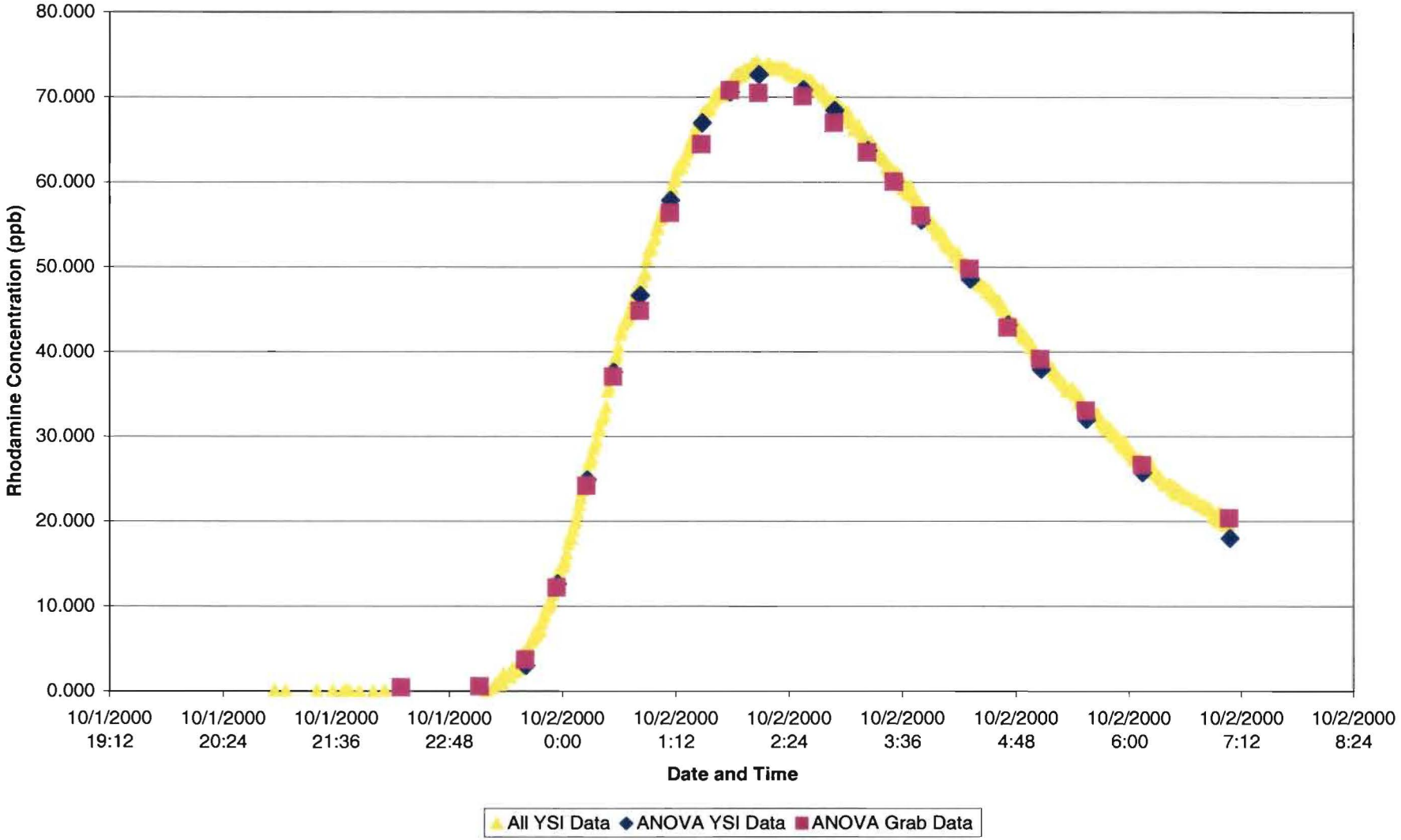
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Innis Road (Injection at S.R. 161)



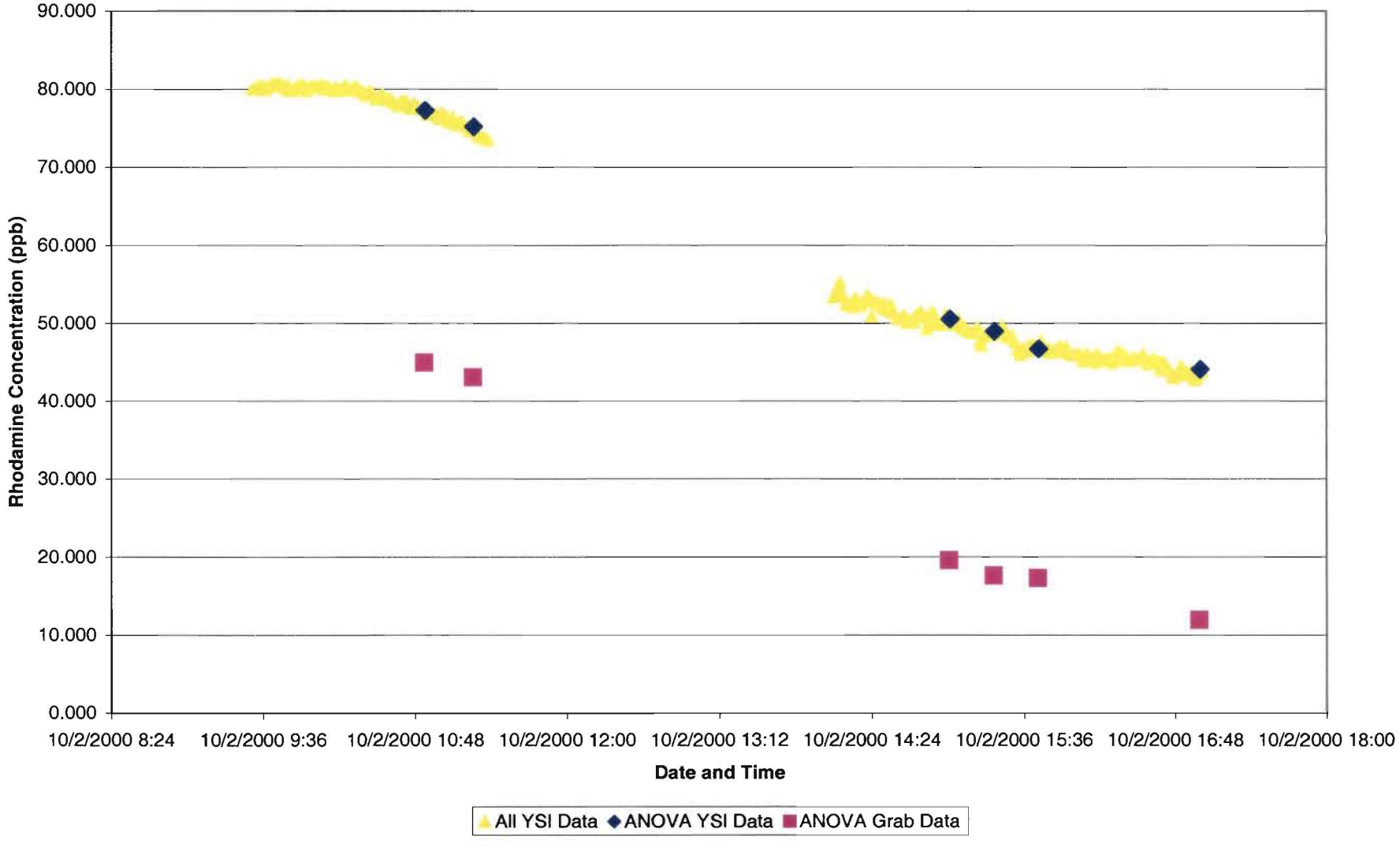
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Rowe Road (Injection at S.R. 317)



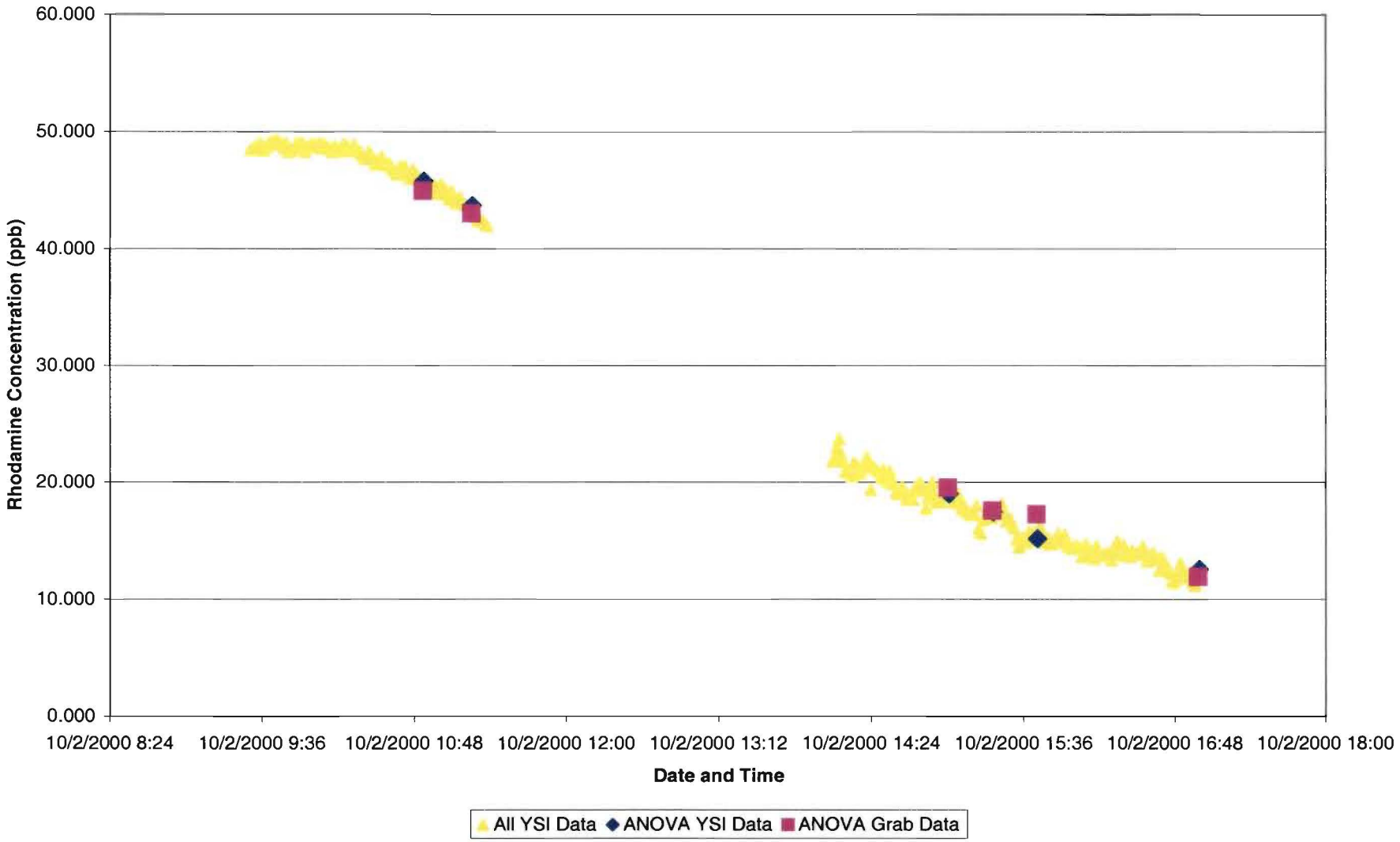
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Rowe Road (Injection at S.R. 317)



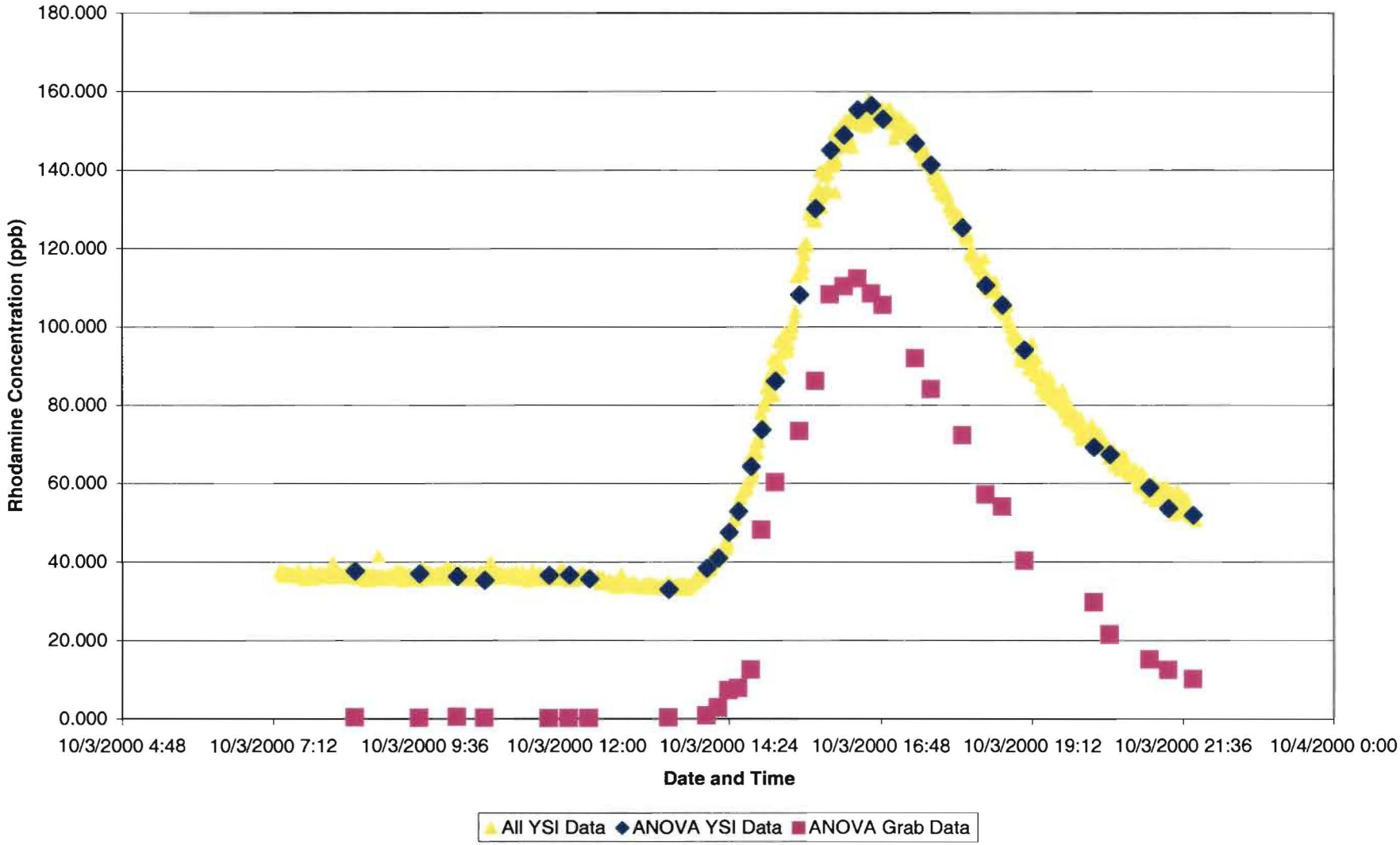
Appendix B Dry Weather Data
Pre-Background Subtraction Curve at S.R. 23 (Injection at S.R. 317)



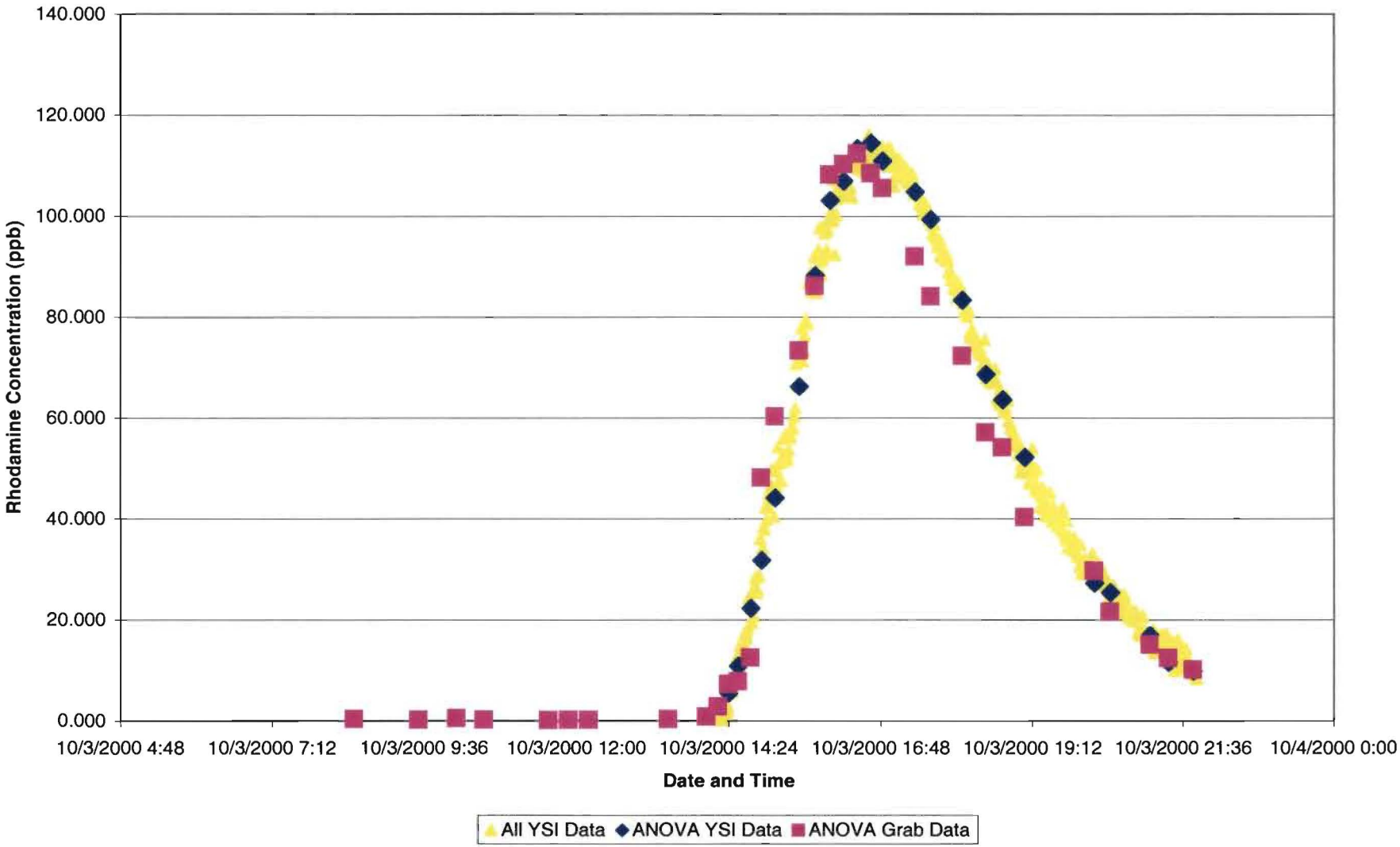
Appendix B Dry Weather Data
Post-Background Subtraction Curve at S.R. 23 (Injection at S.R. 317)



Appendix B Dry Weather Data
Pre-Background Subtraction Curve at Williams Road (Injection at Watkins Road)



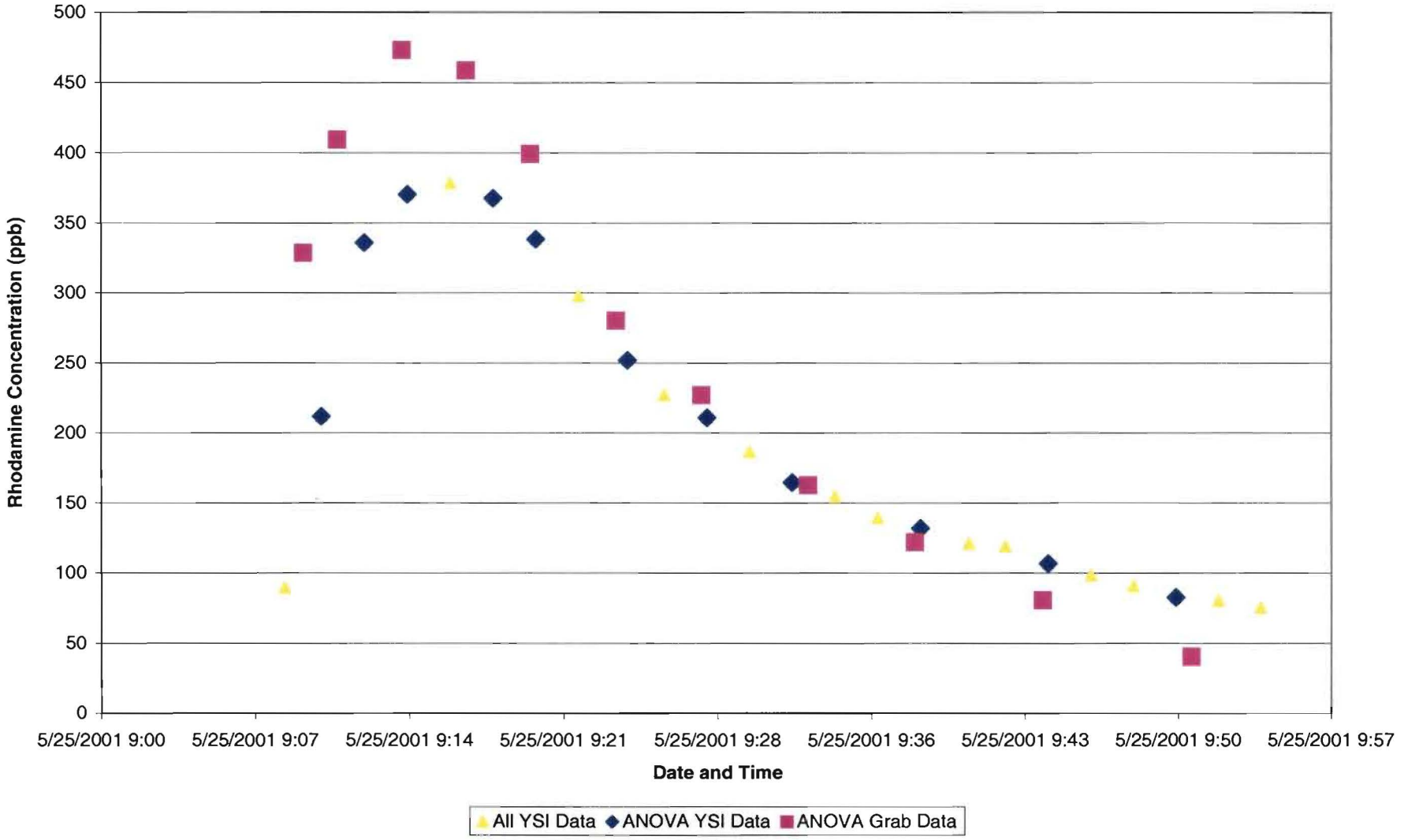
Appendix B Dry Weather Data
Post-Background Subtraction Curve at Williams Road (Injection at Watkins Road)



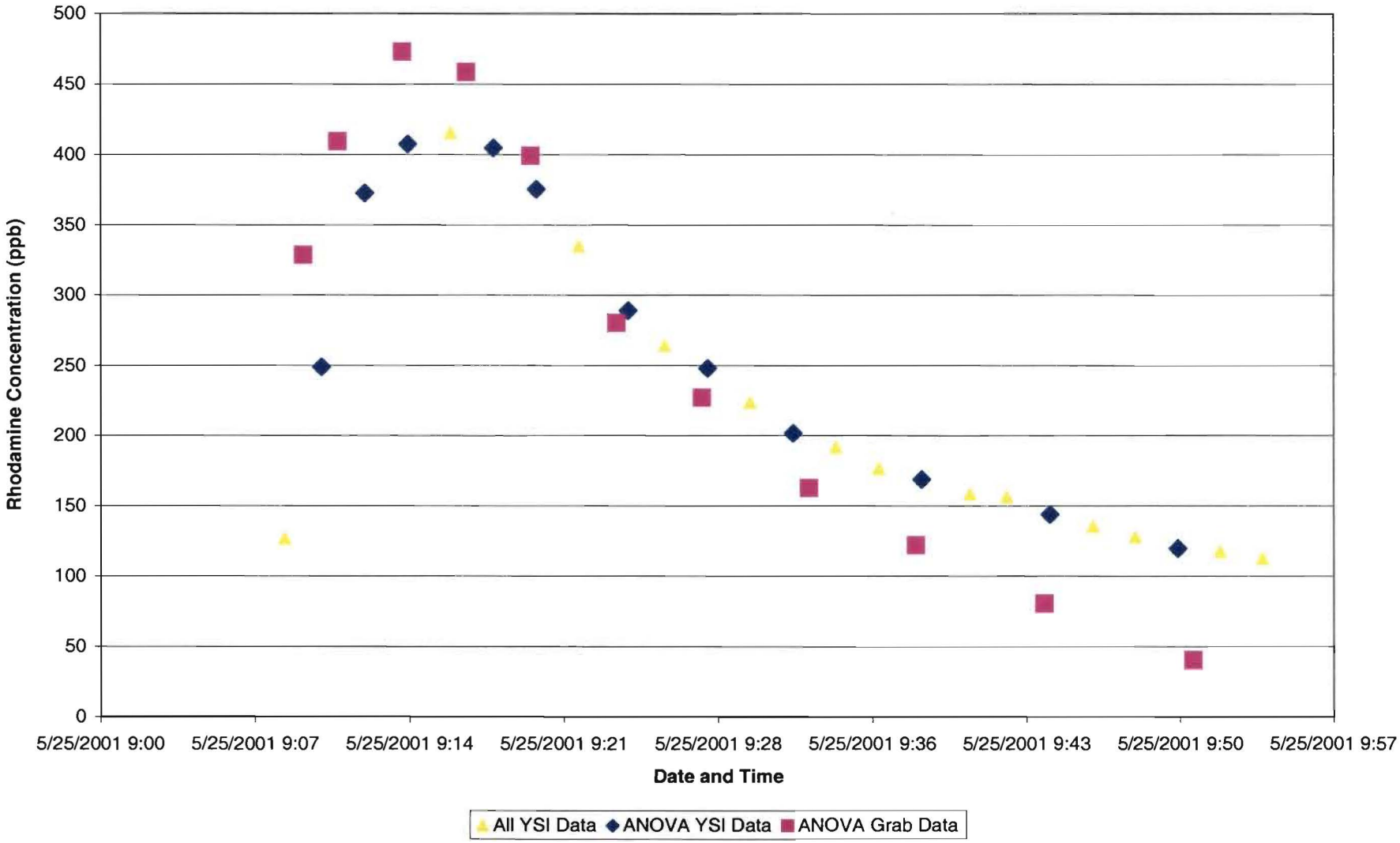
Appendix C

Wet Weather Data

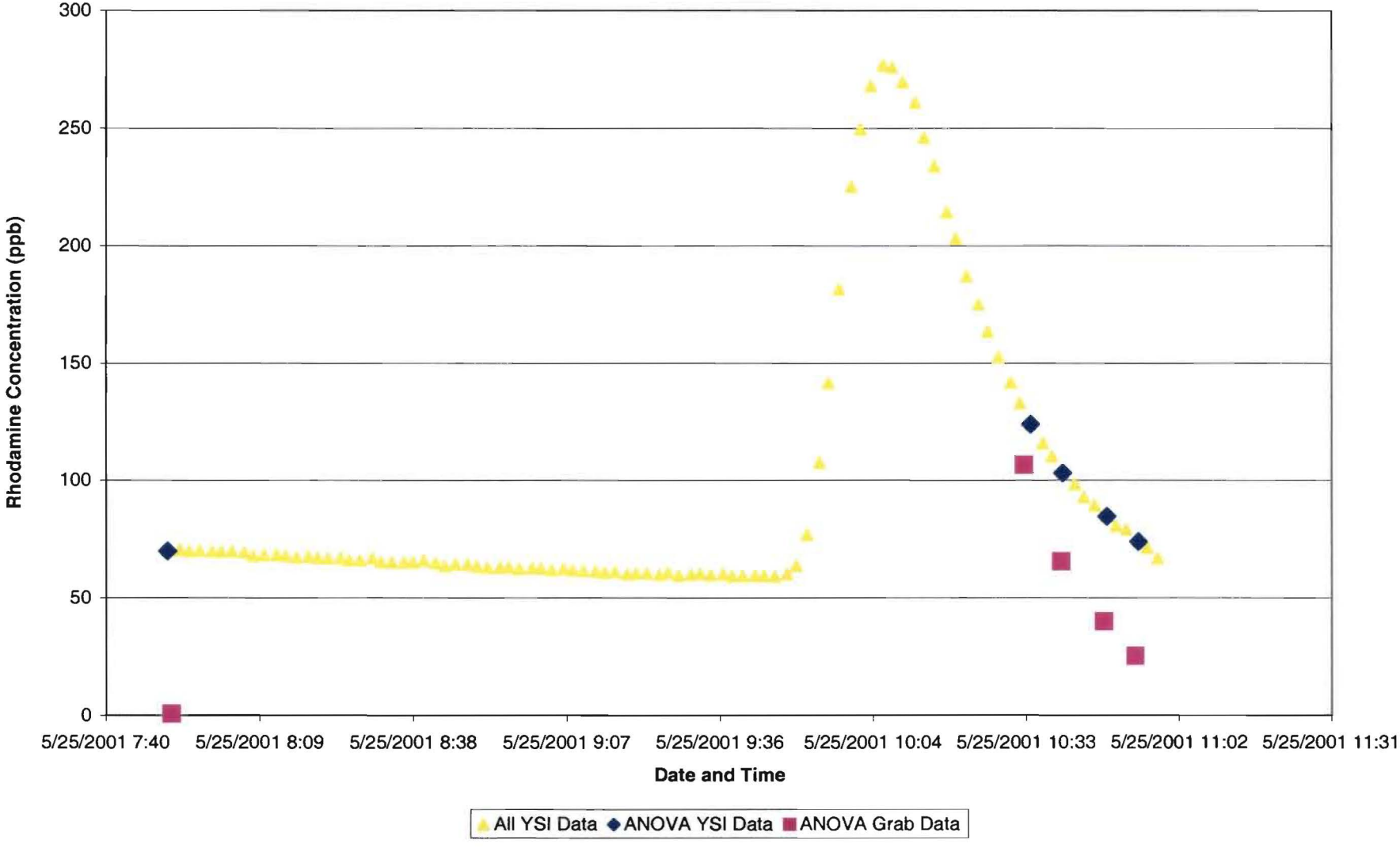
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Schrock Road (Injection at Main Street-Westerville)



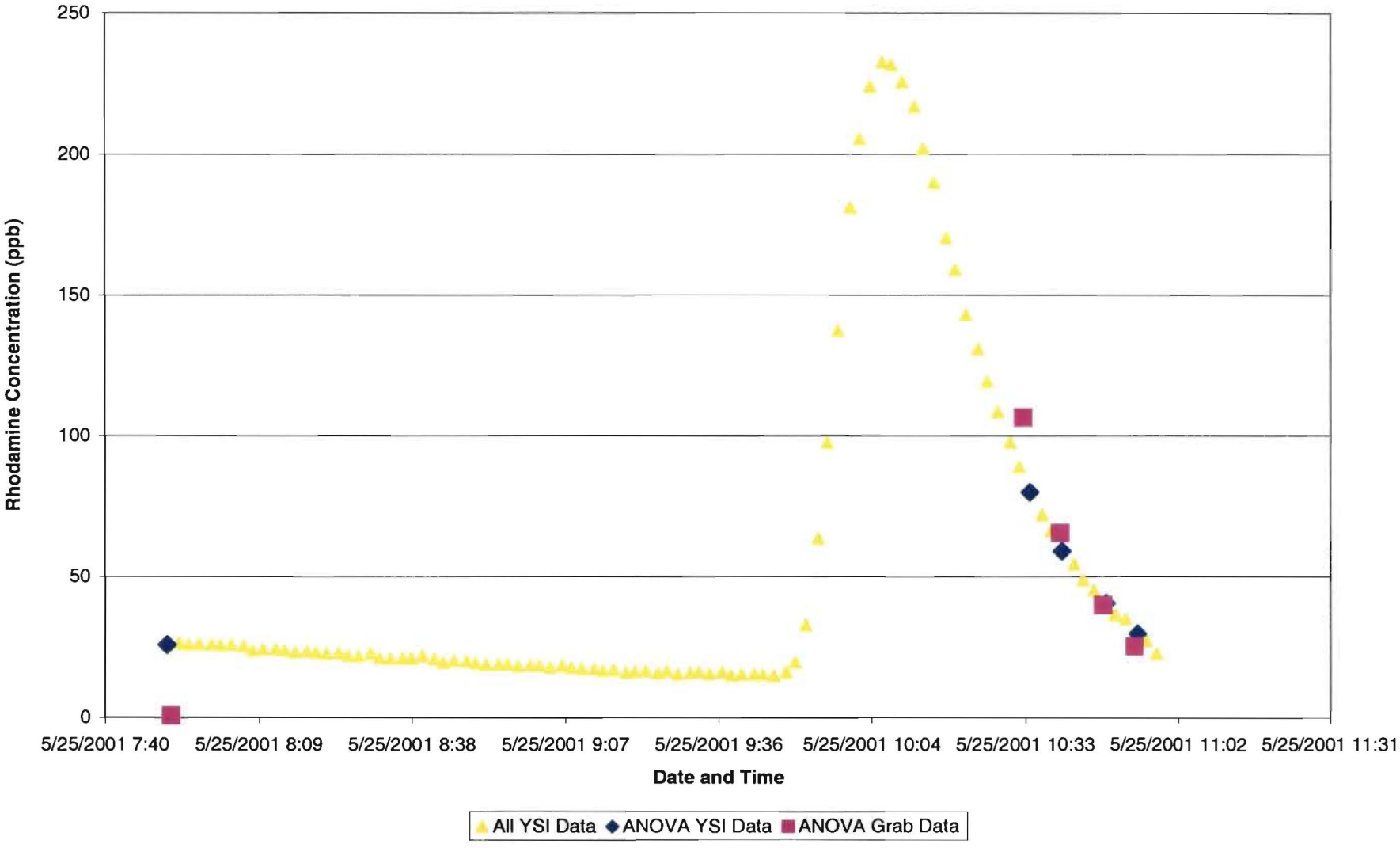
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Schrock Road (Injection at Main Street-Westerville)



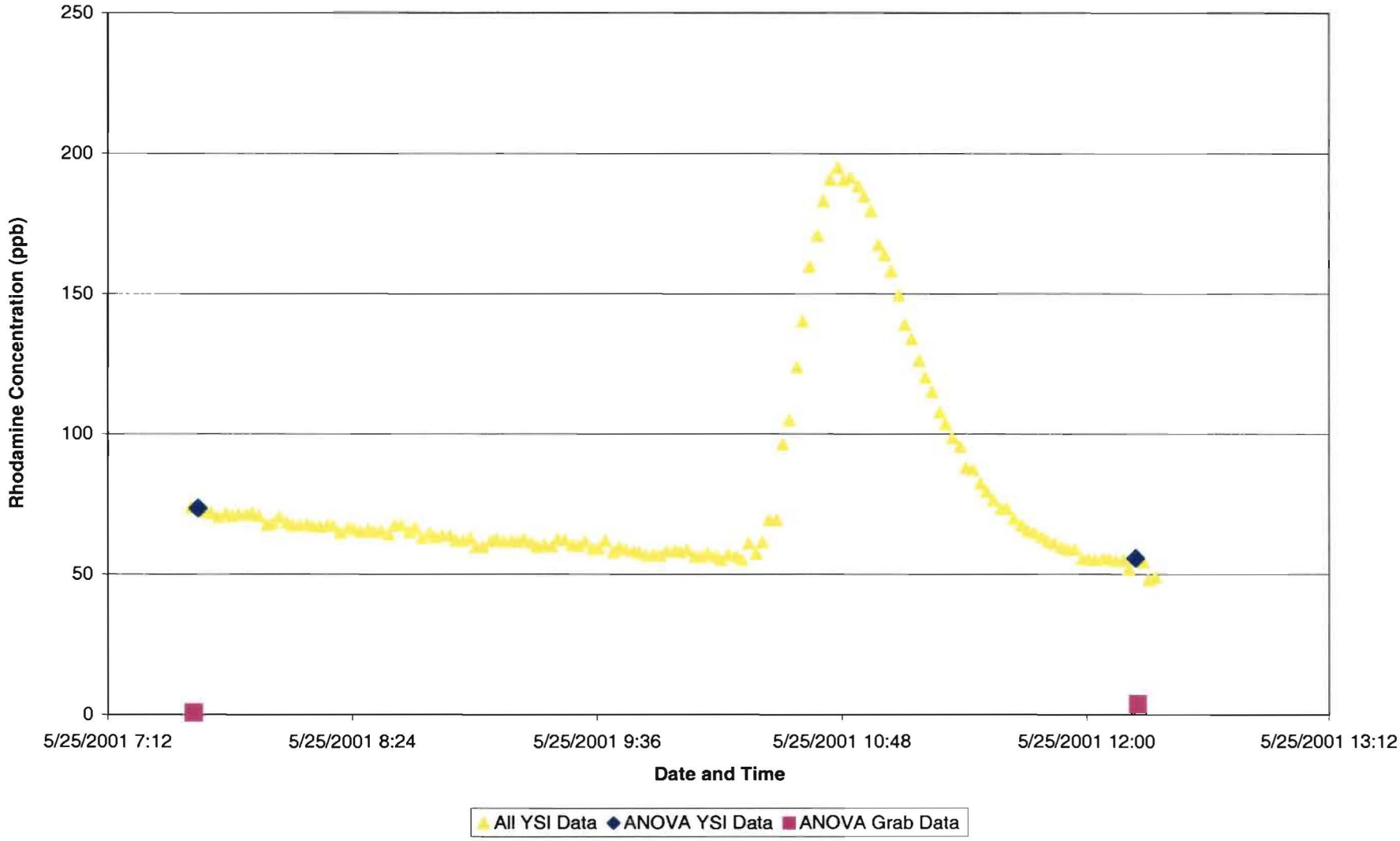
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Route 3 (Injection at Main Street-Westerville)



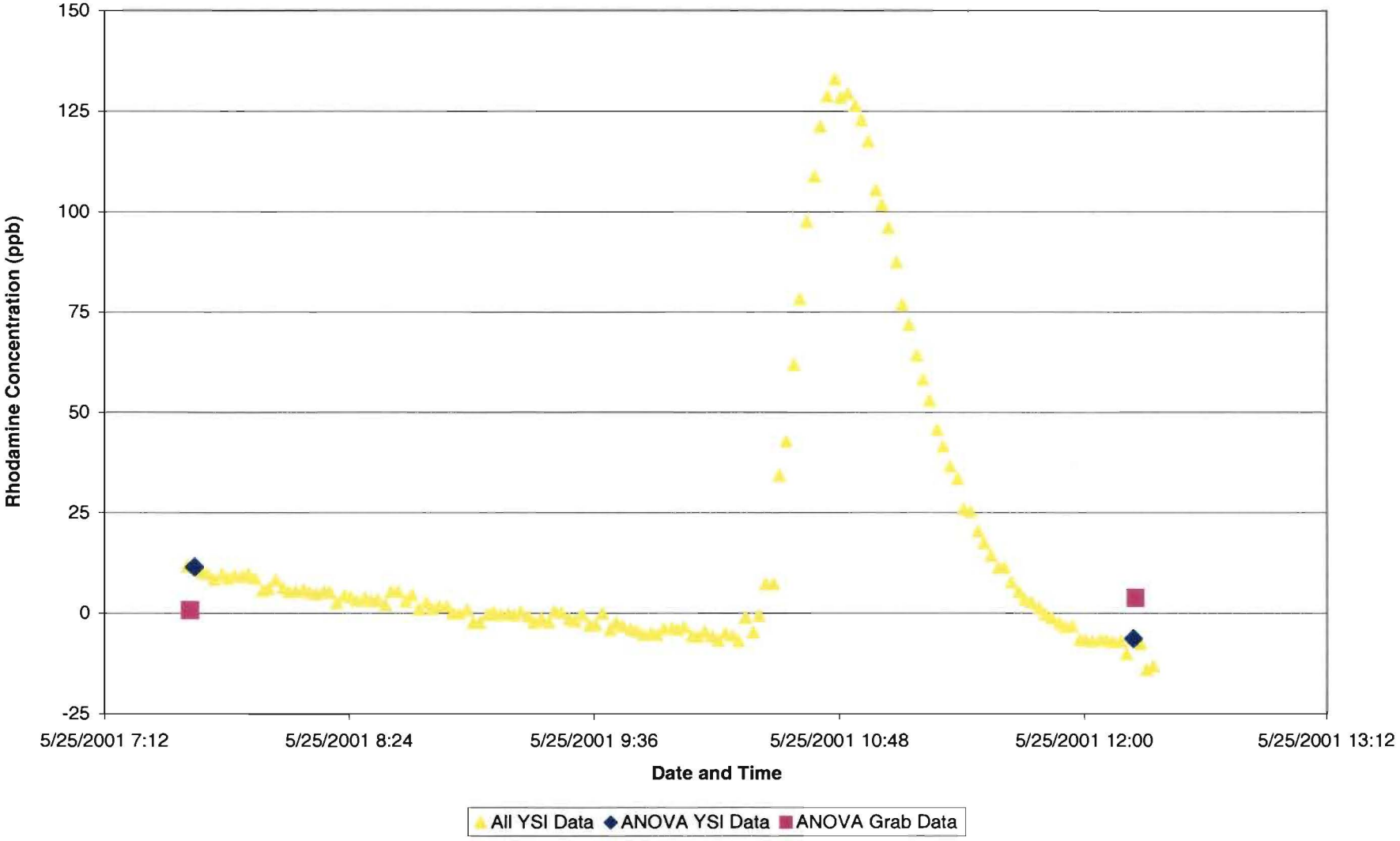
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Route 3 (Injection at Main Street-Westerville)



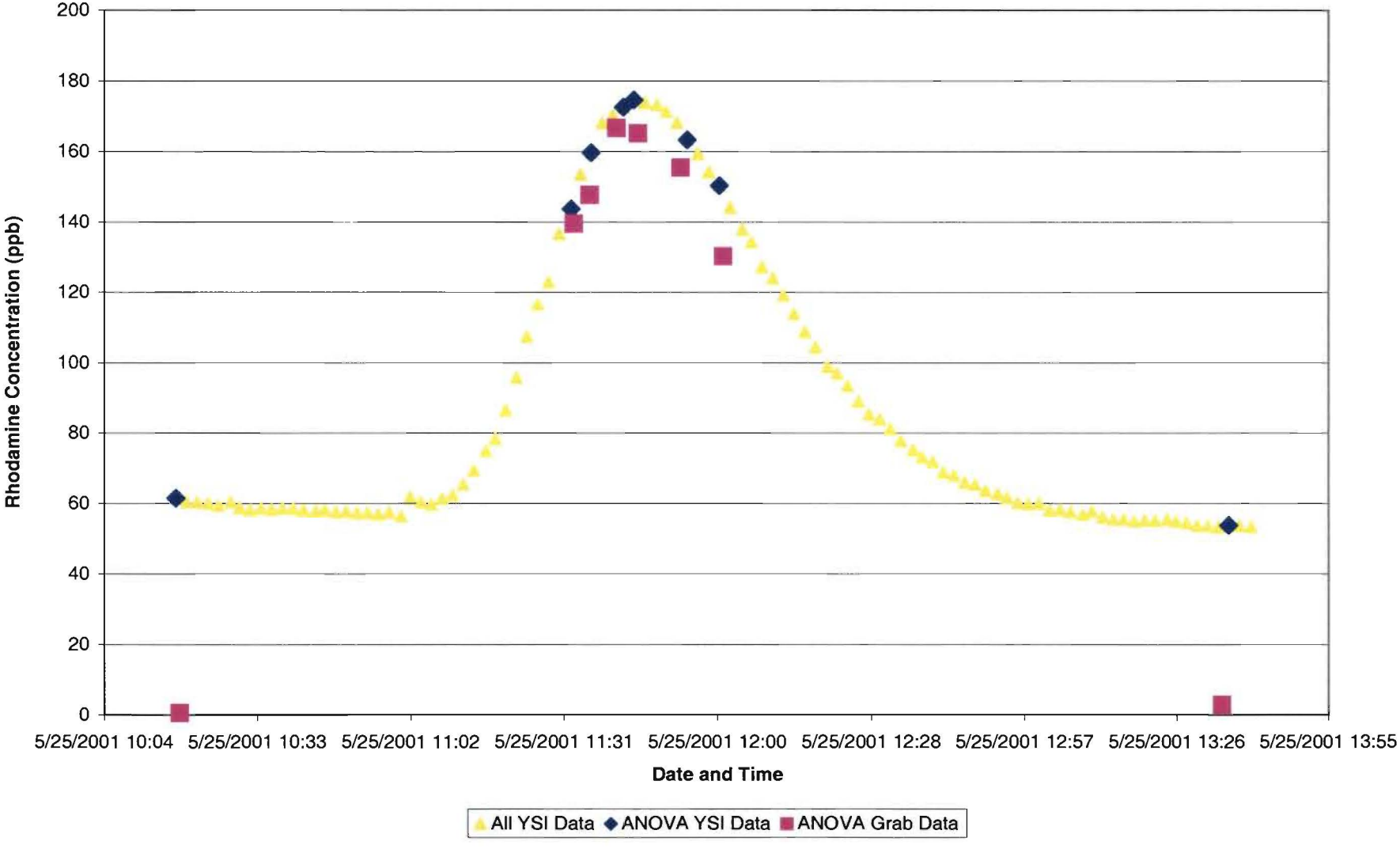
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at S.R. 161 (Injection at Main Street-Westerville)



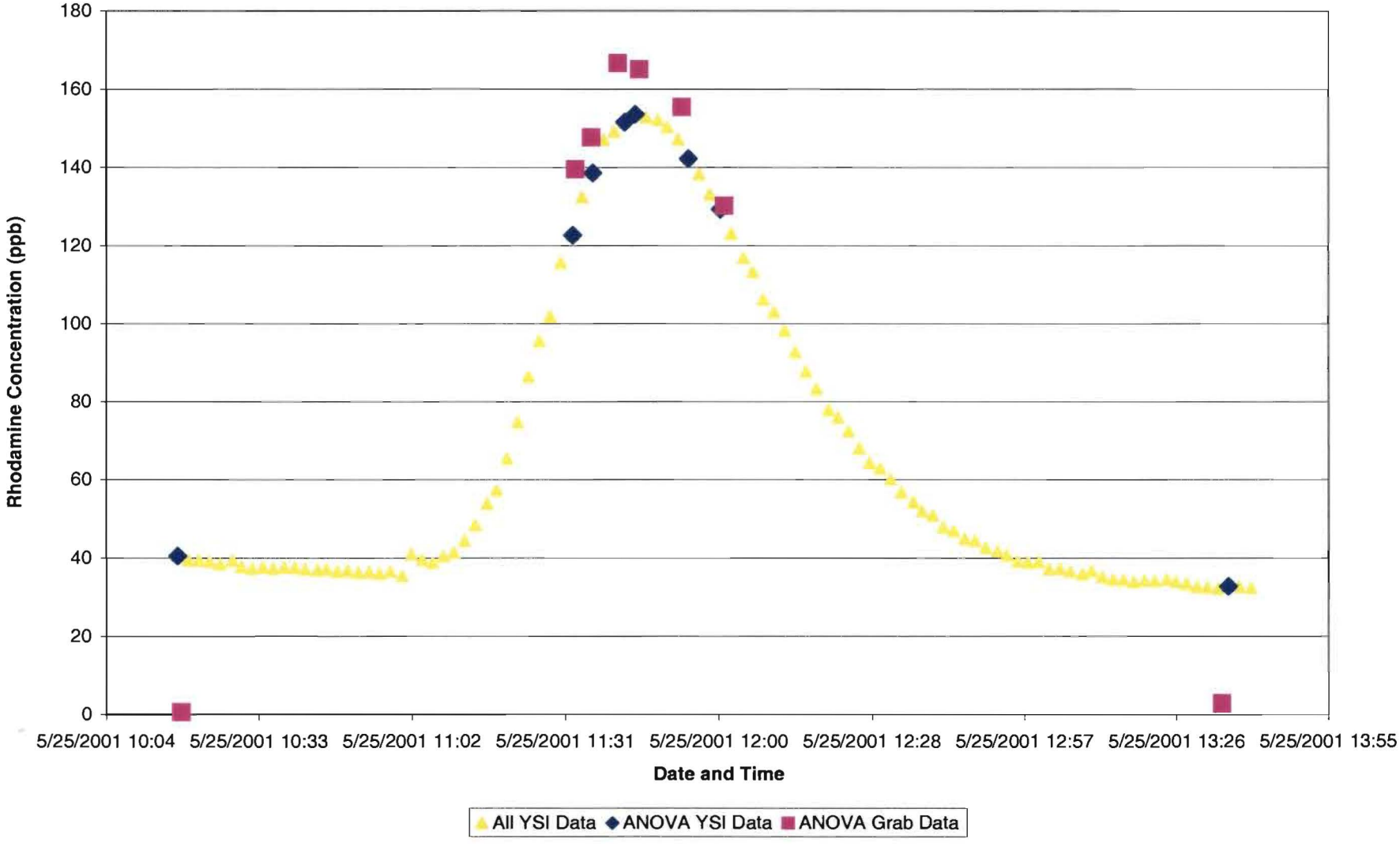
Appendix C Wet Weather Data
Post-Background Subtraction Curve at S.R. 161 (Injection at Main Street-Westerville)



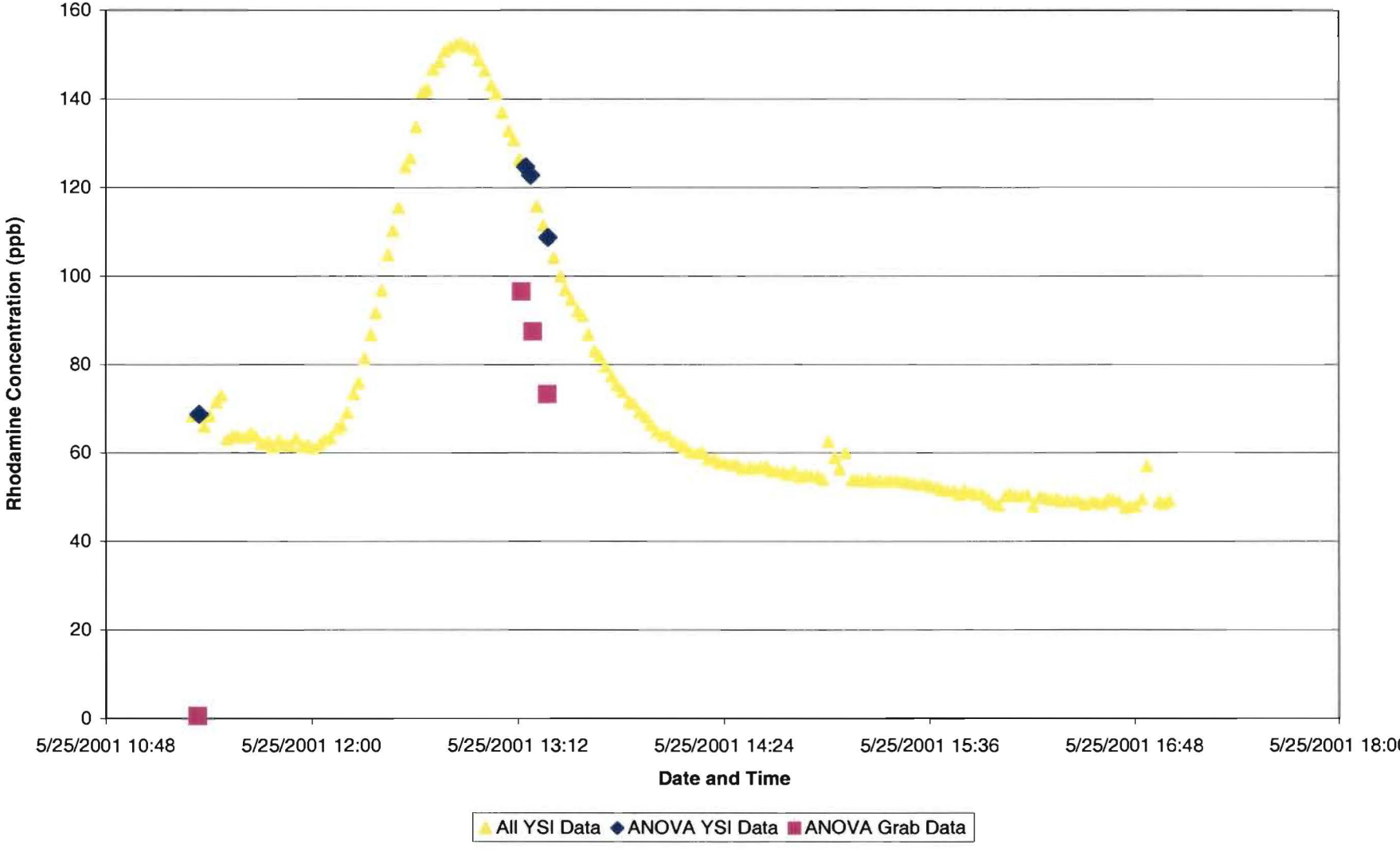
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Morse Road (Injection at Main Street-Westerville)



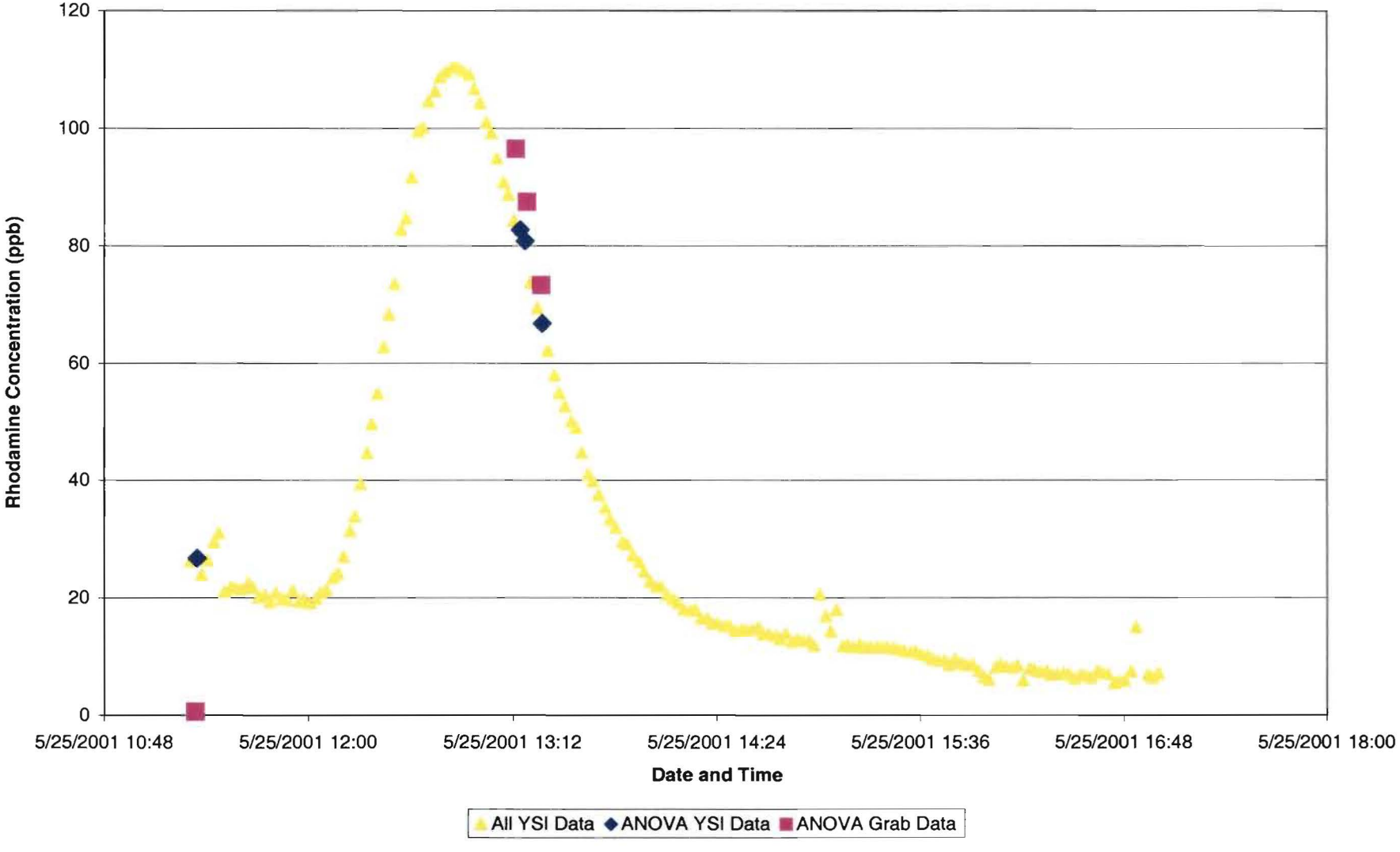
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Morse Road (Injection at Main Street-Westerville)



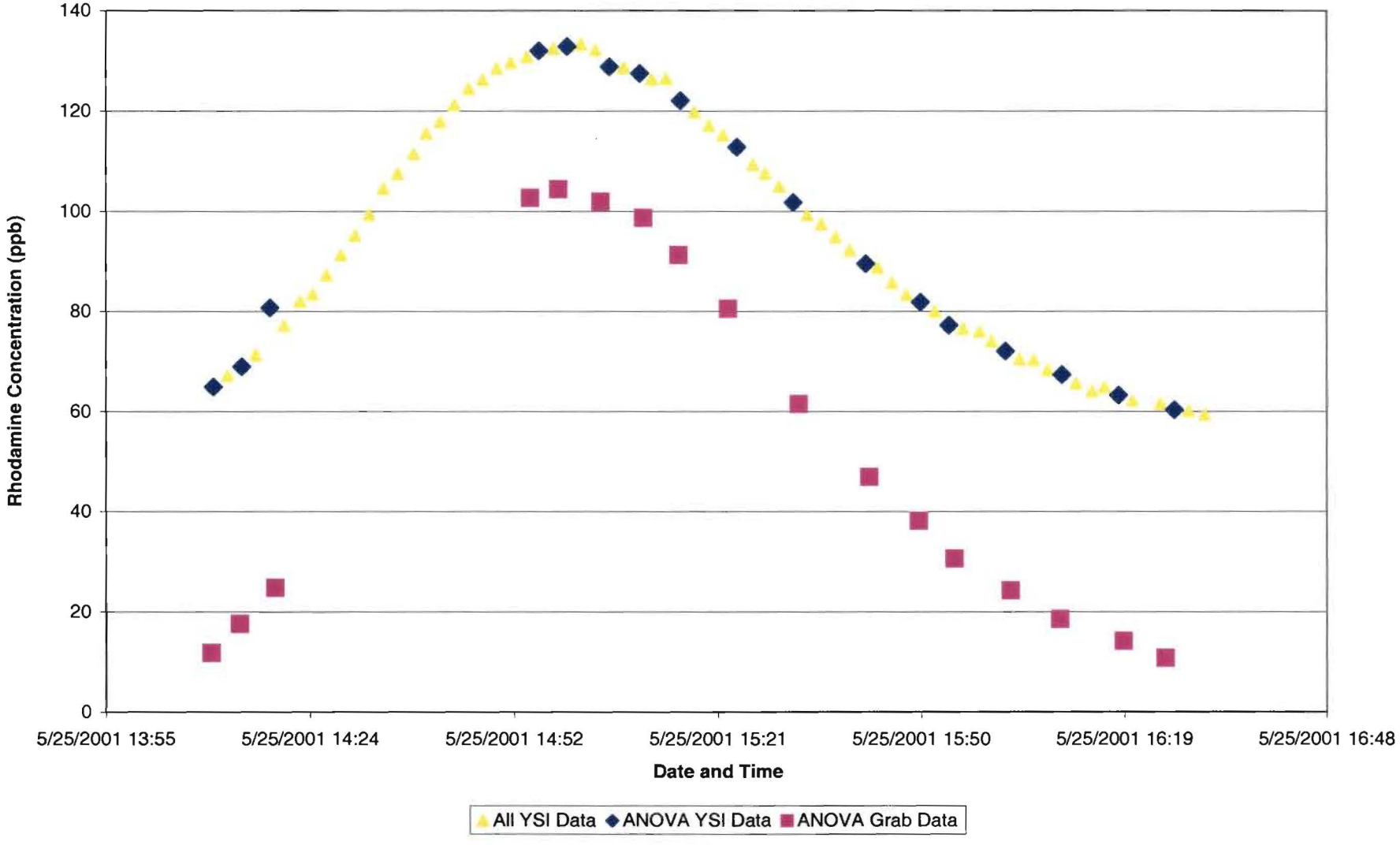
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Innis Road (Injection at Main Street-Westerville)



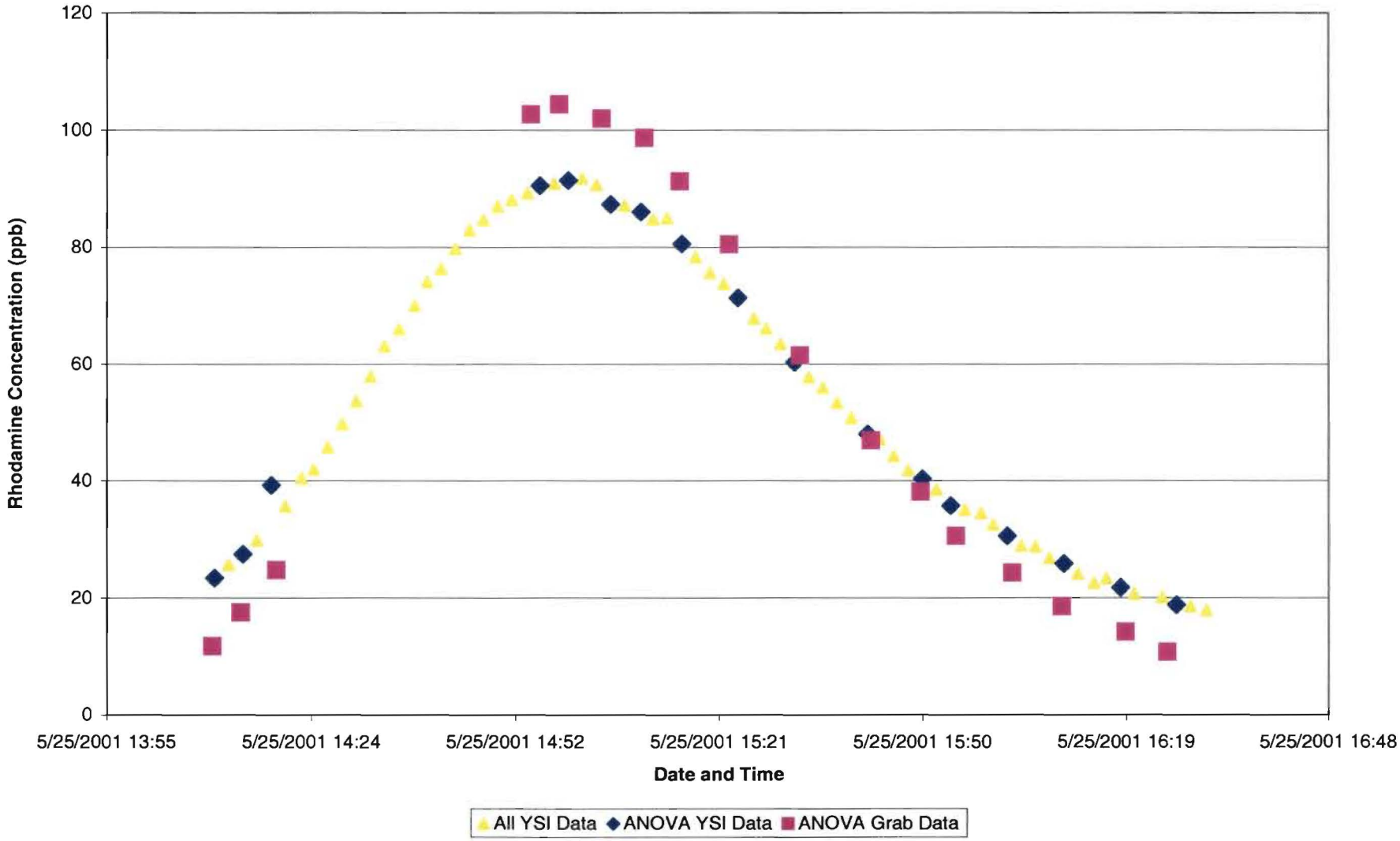
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Innis Road (Injection at Main Street-Westerville)



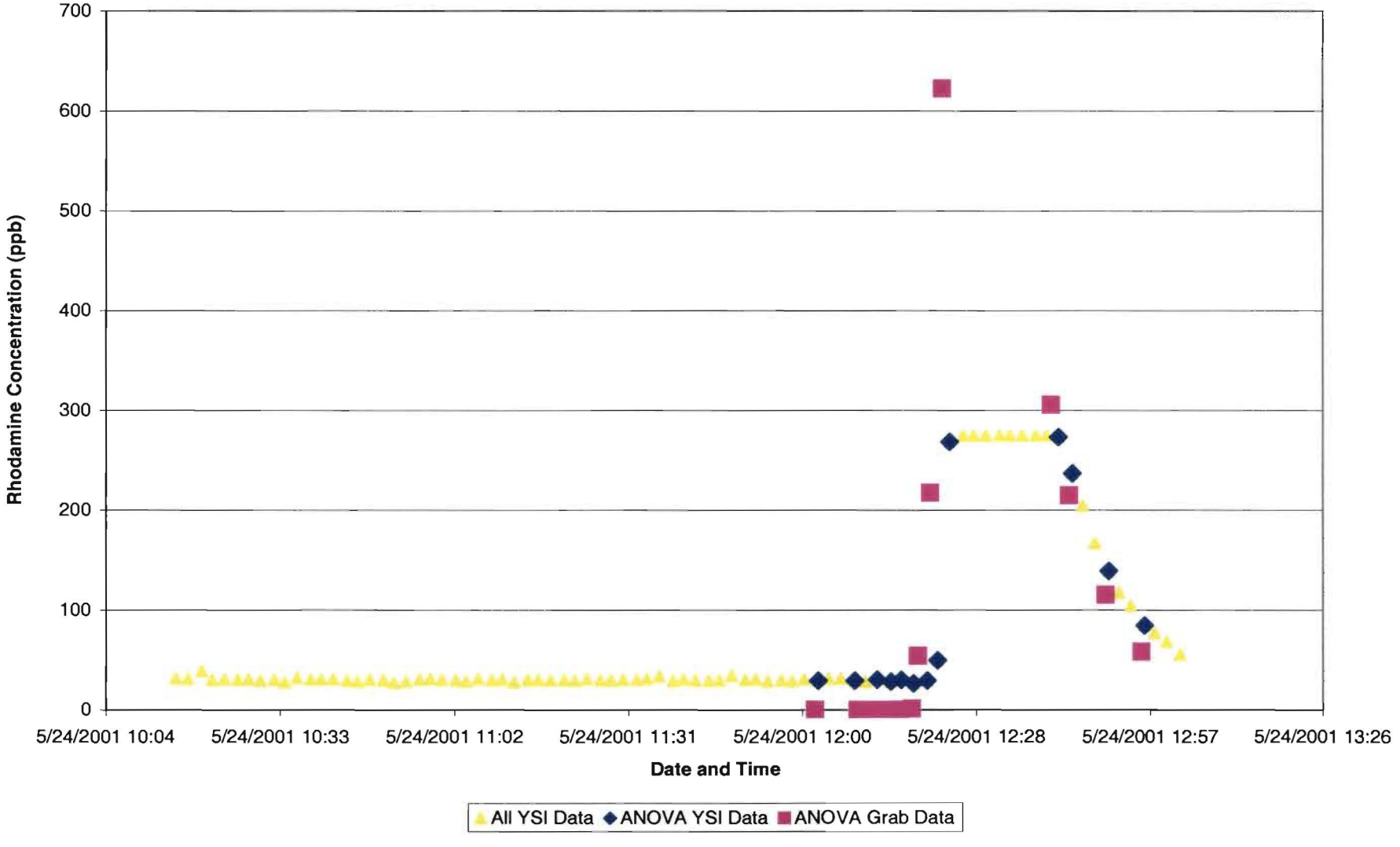
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Airport Road (Injection at Main Street-Westerville)



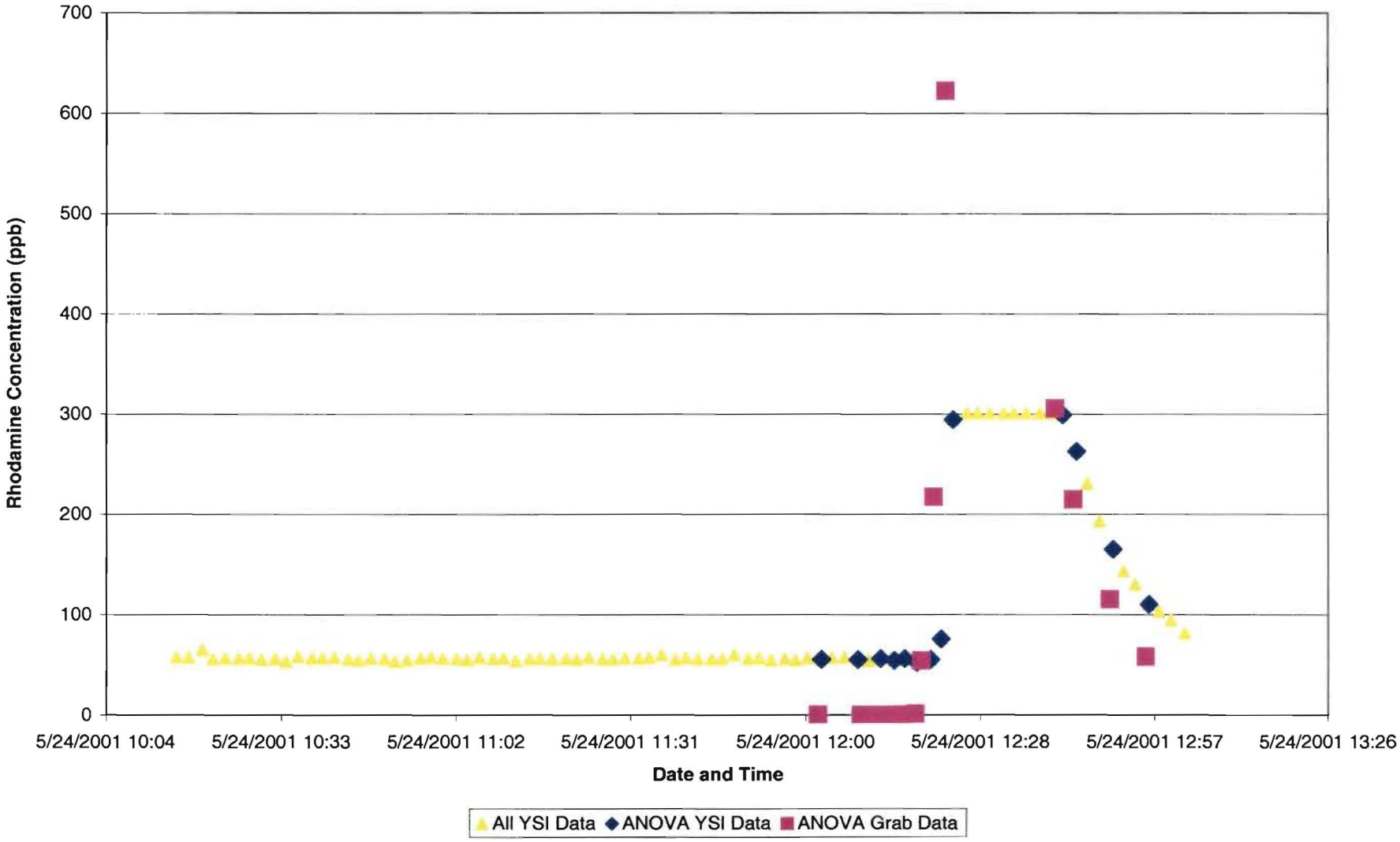
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Airport Road (Injection at Main Street-Westerville)



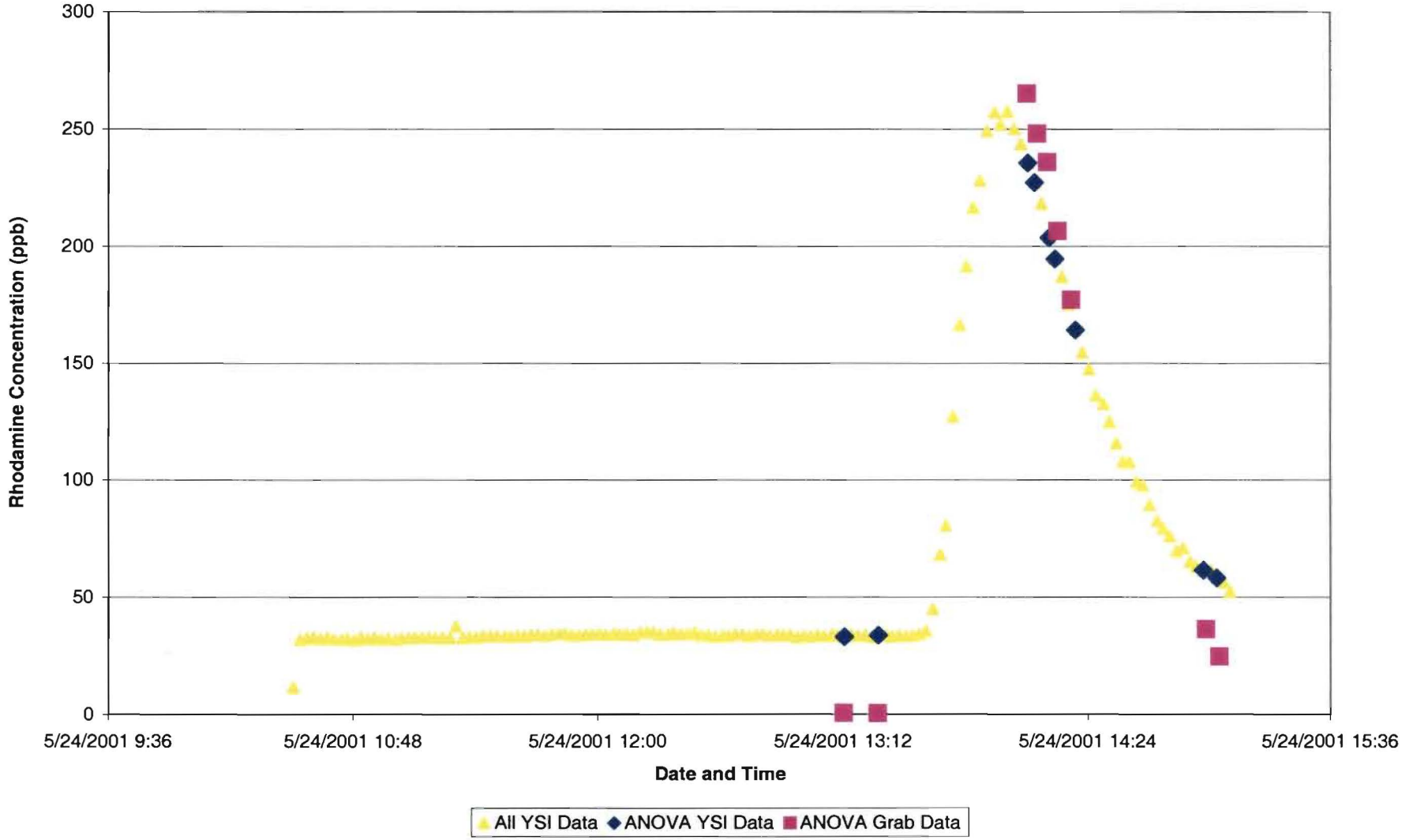
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Airport Road (Injection at Mock Road)



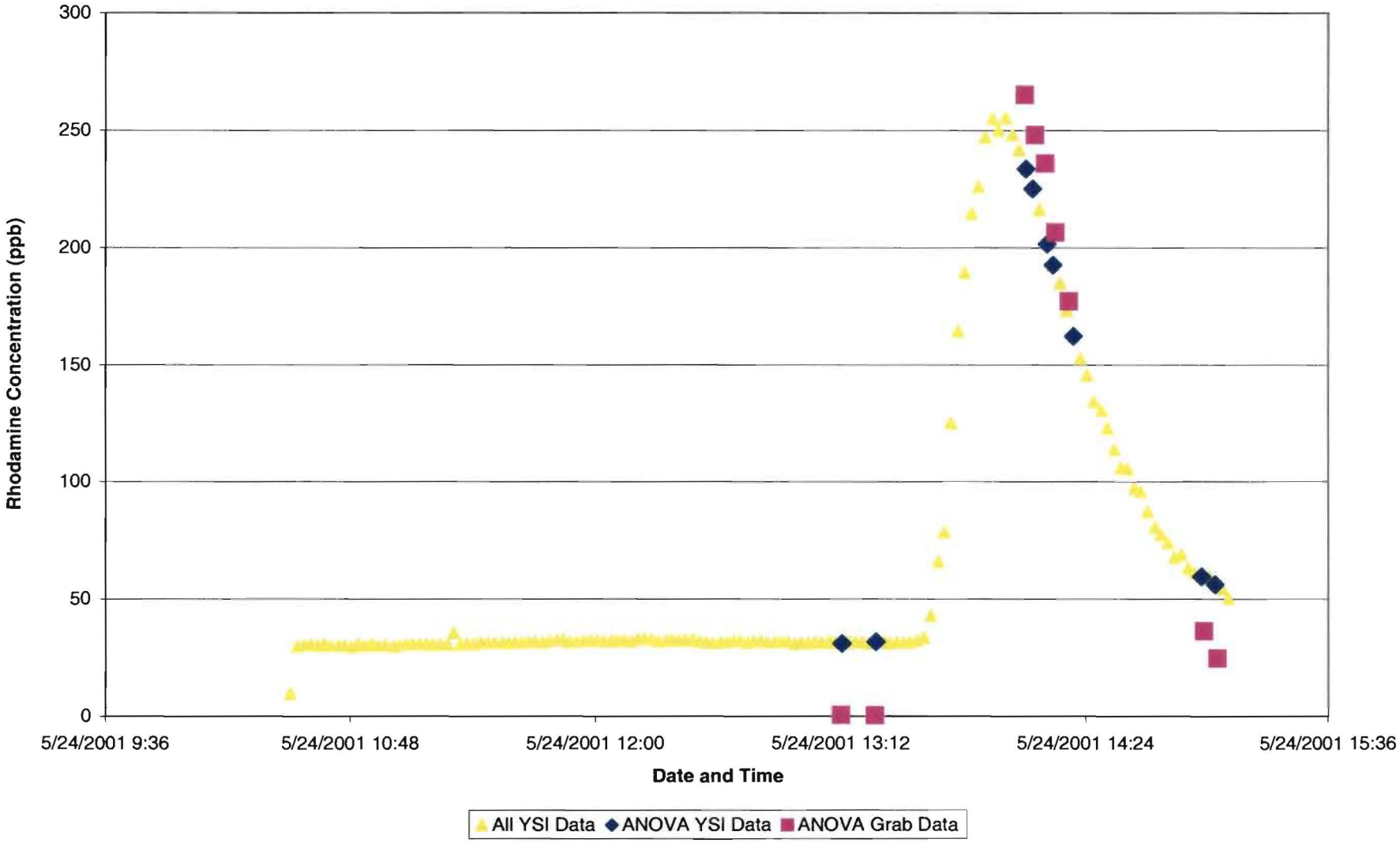
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Airport Road (Injection at Mock Road)



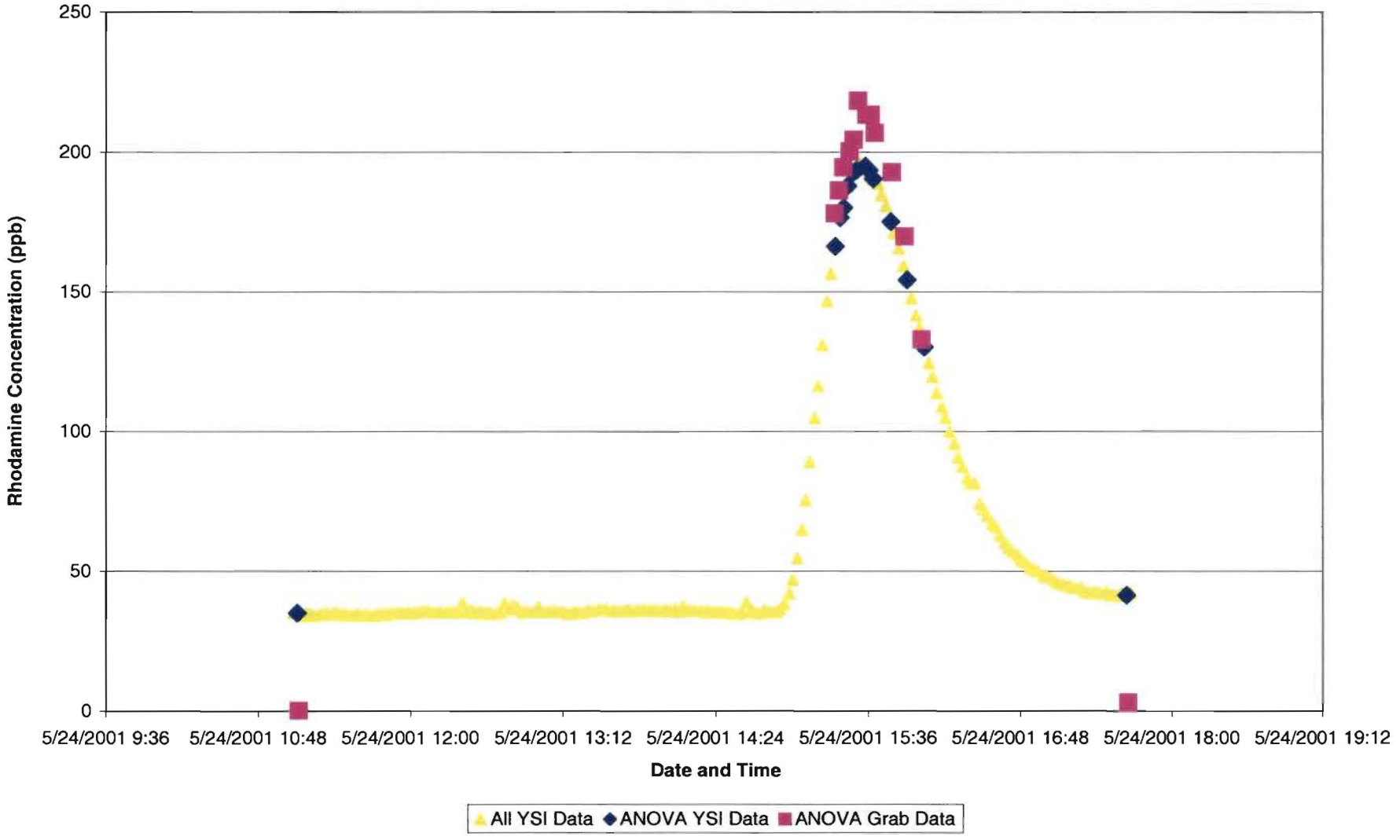
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Clifton Avenue (Injection at Mock Road)



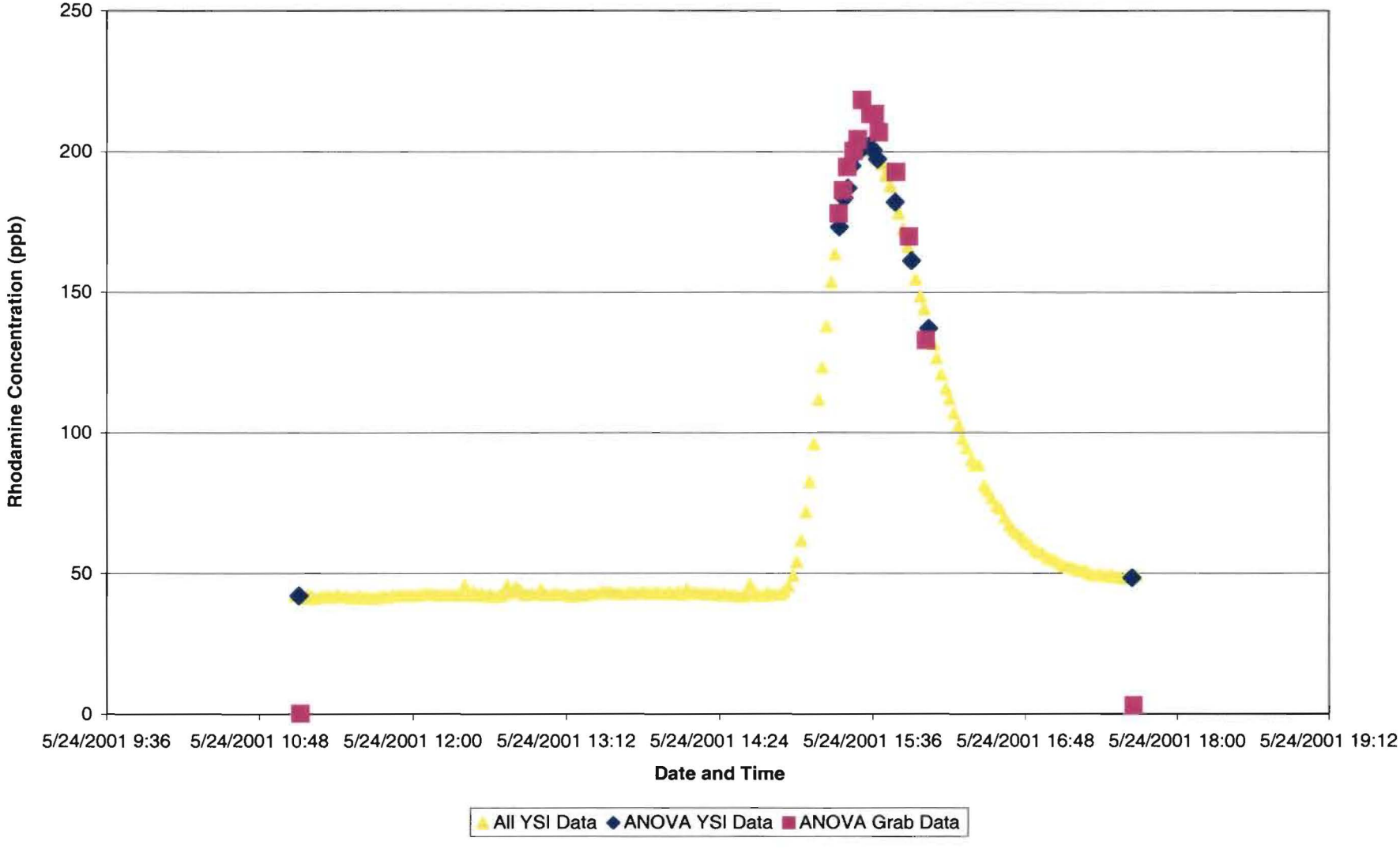
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Clifton Avenue (Injection at Mock Road)



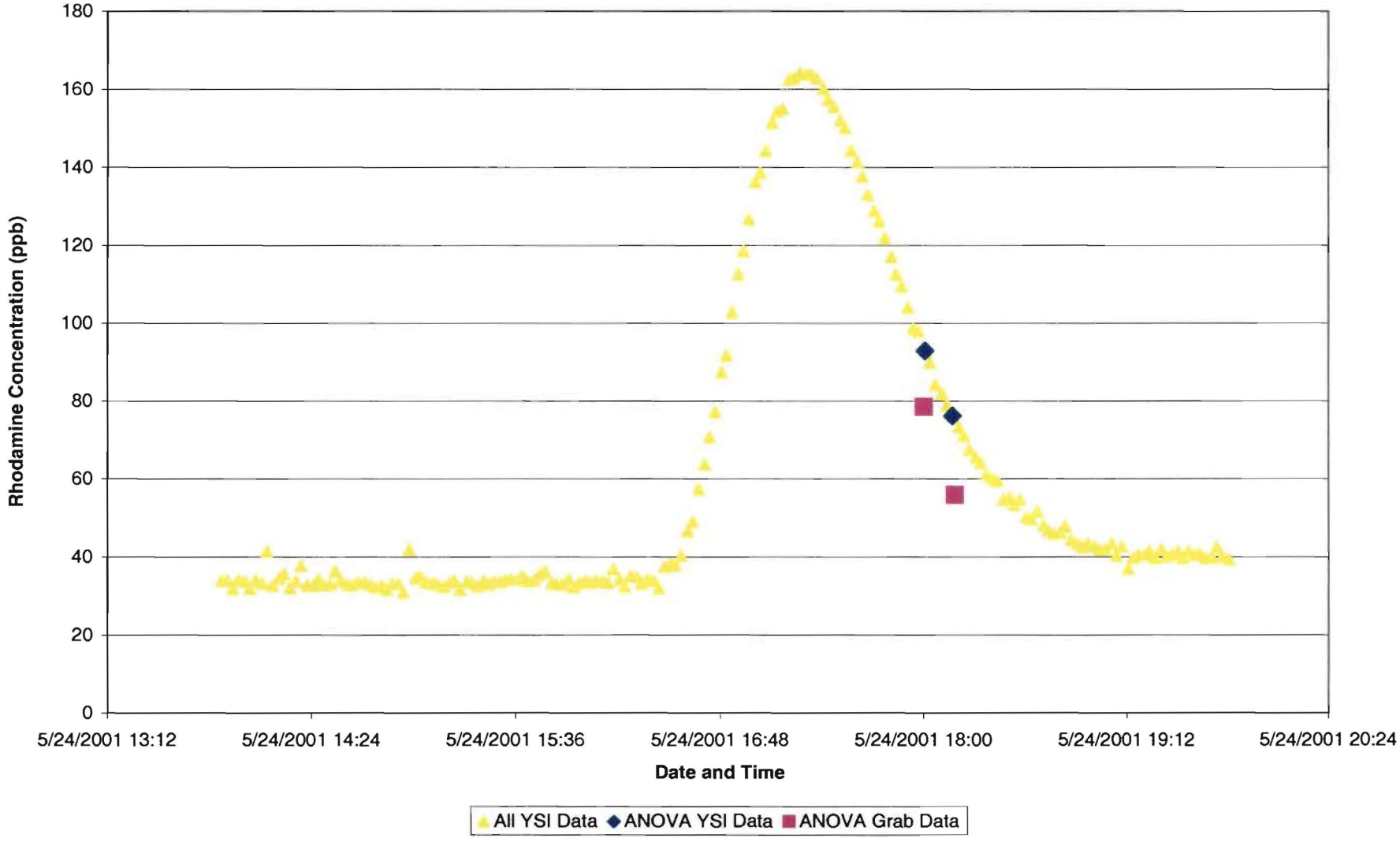
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Livingston Avenue (Injection at Mock Road)



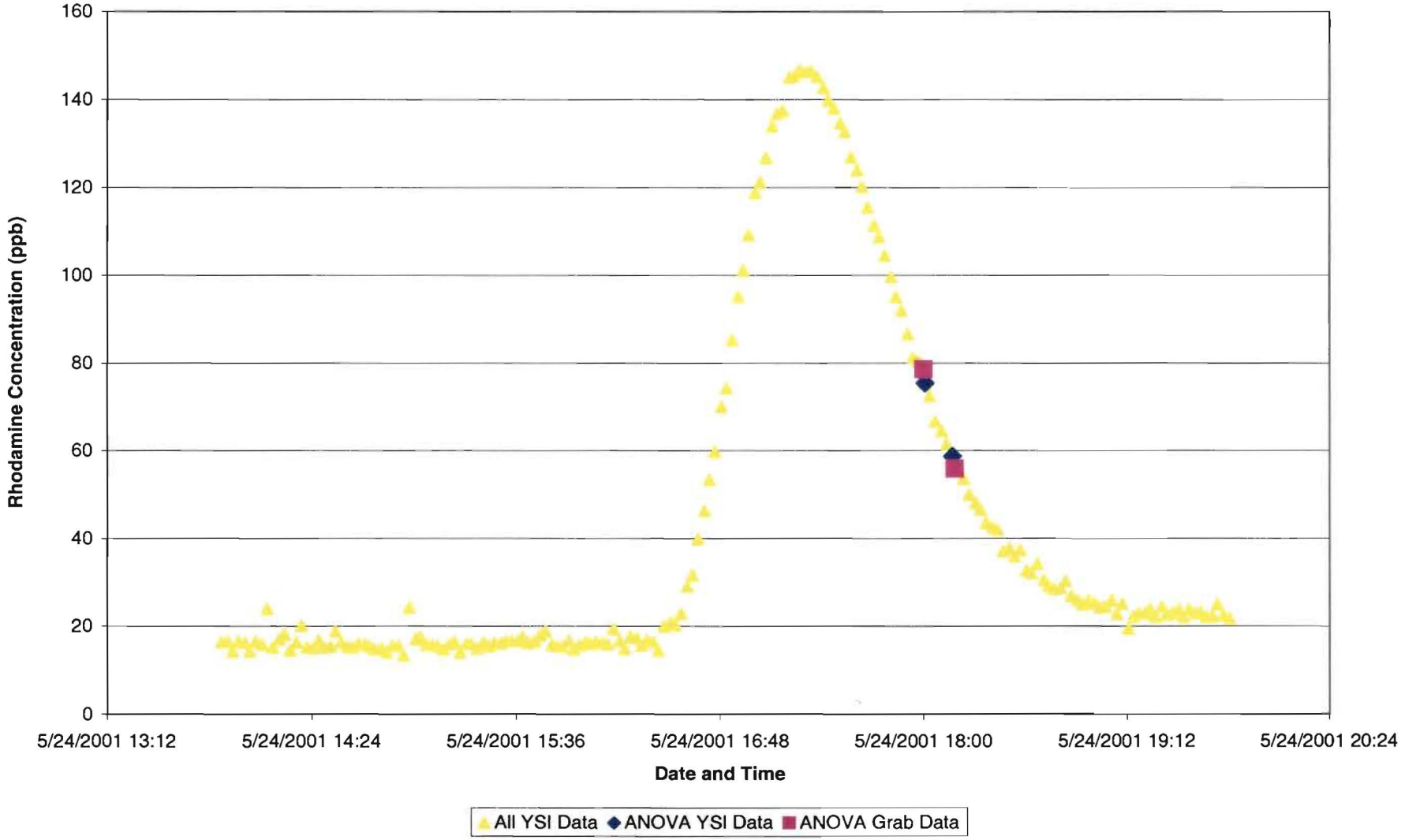
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Livingston Avenue (Injection at Mock Road)



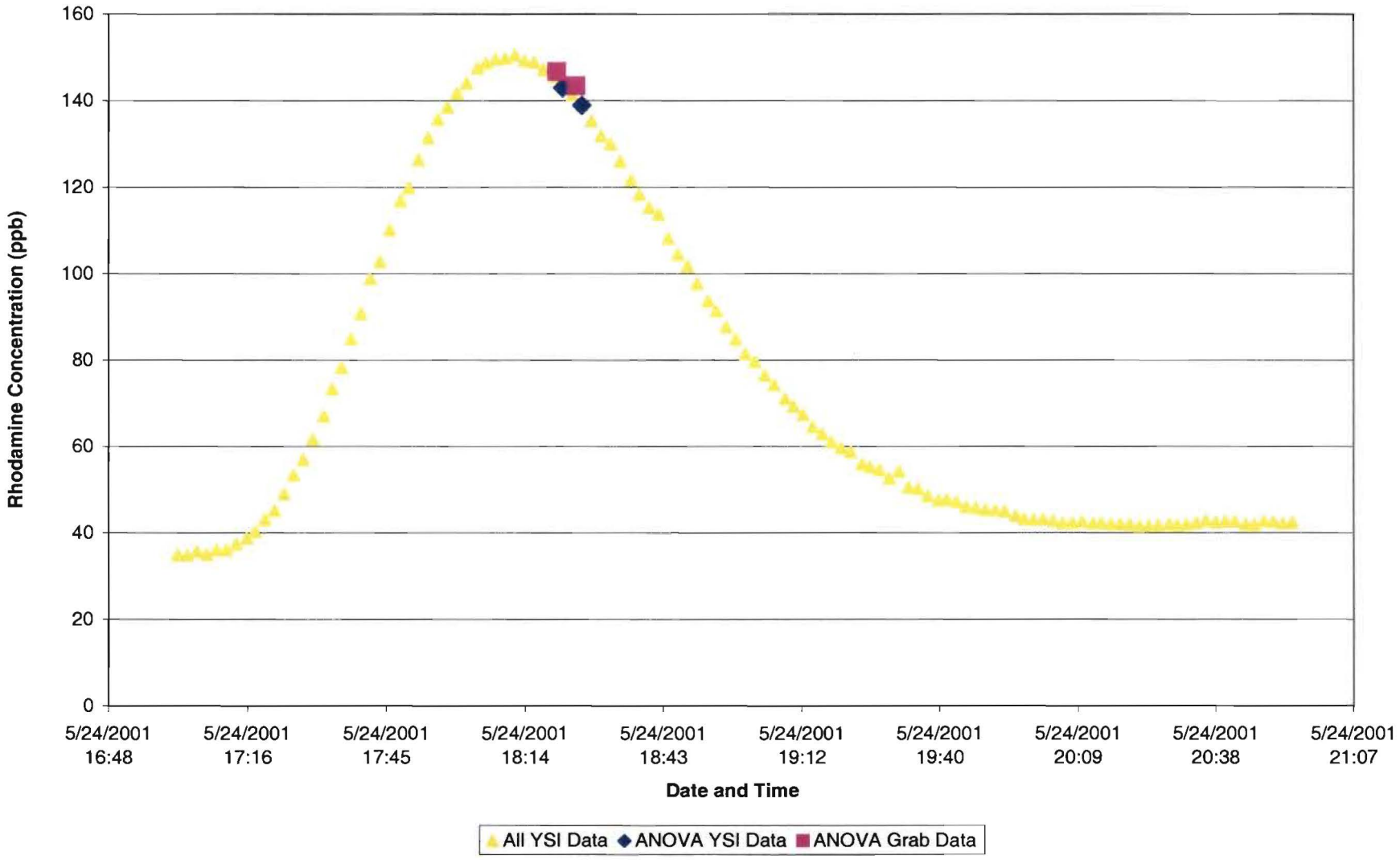
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at S.R. 104 (Injection at Mock Road)



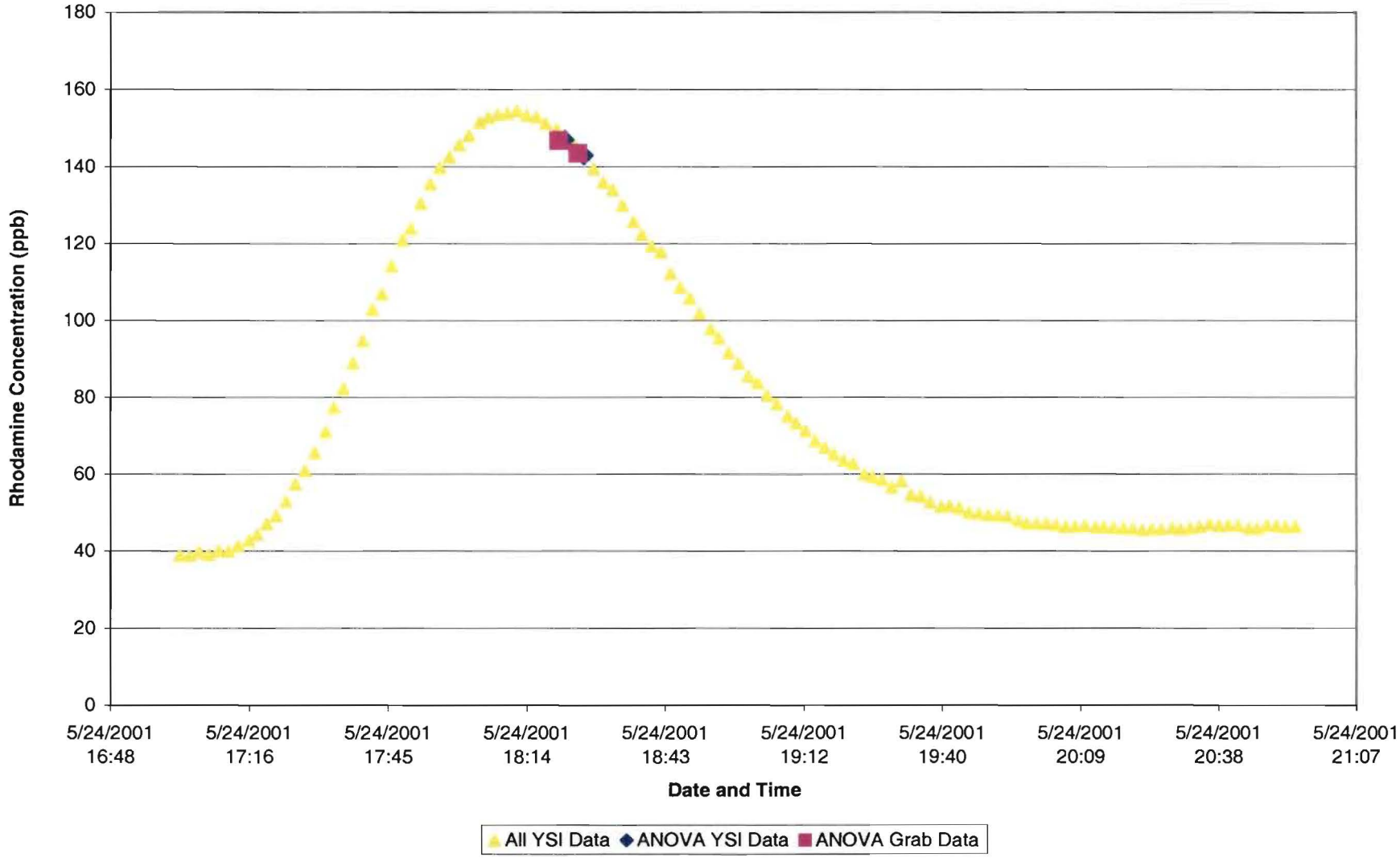
Appendix C Wet Weather Data
Post-Background Subtraction Curve at S.R. 104 (Injection at Mock Road)



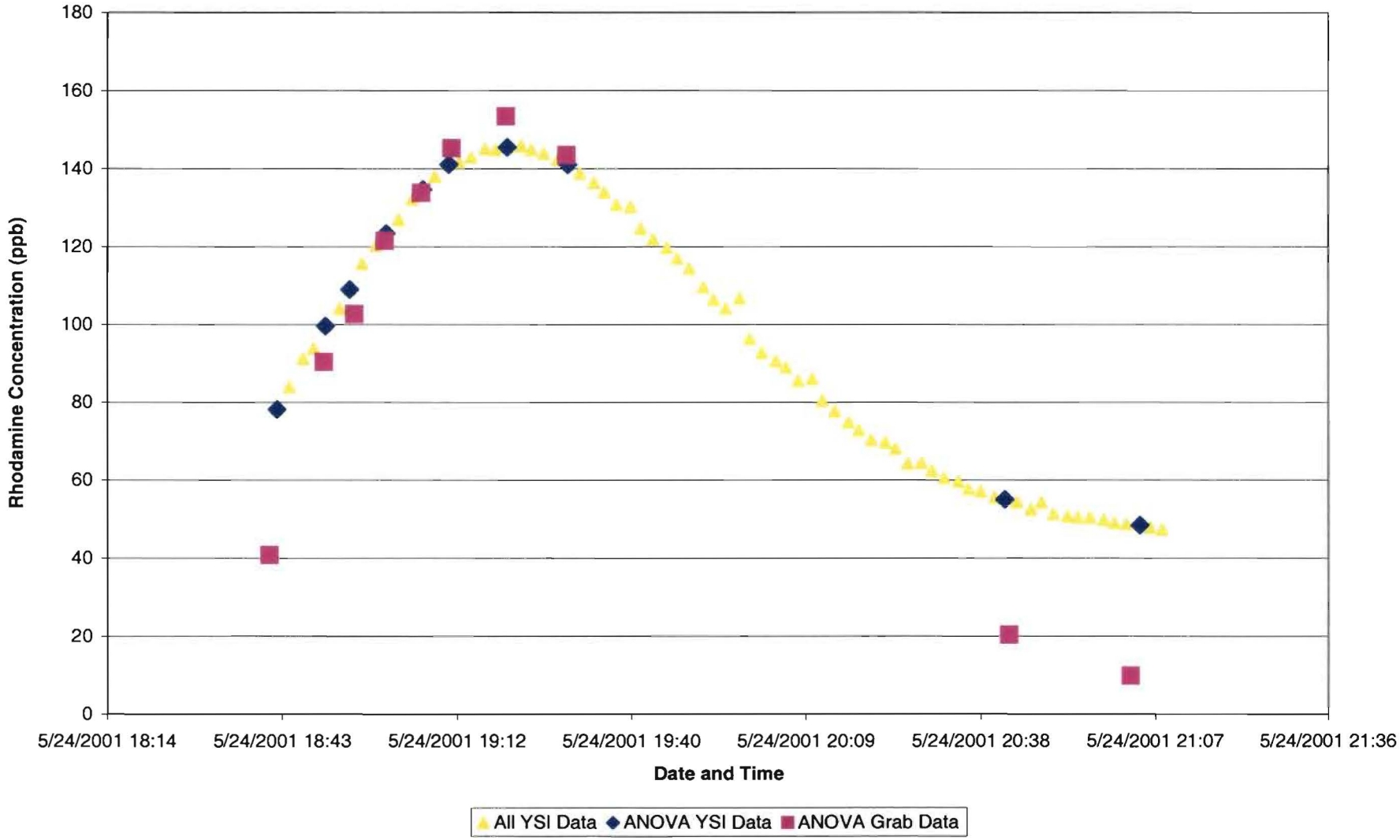
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Watkins Road (Injection at Mock Road)



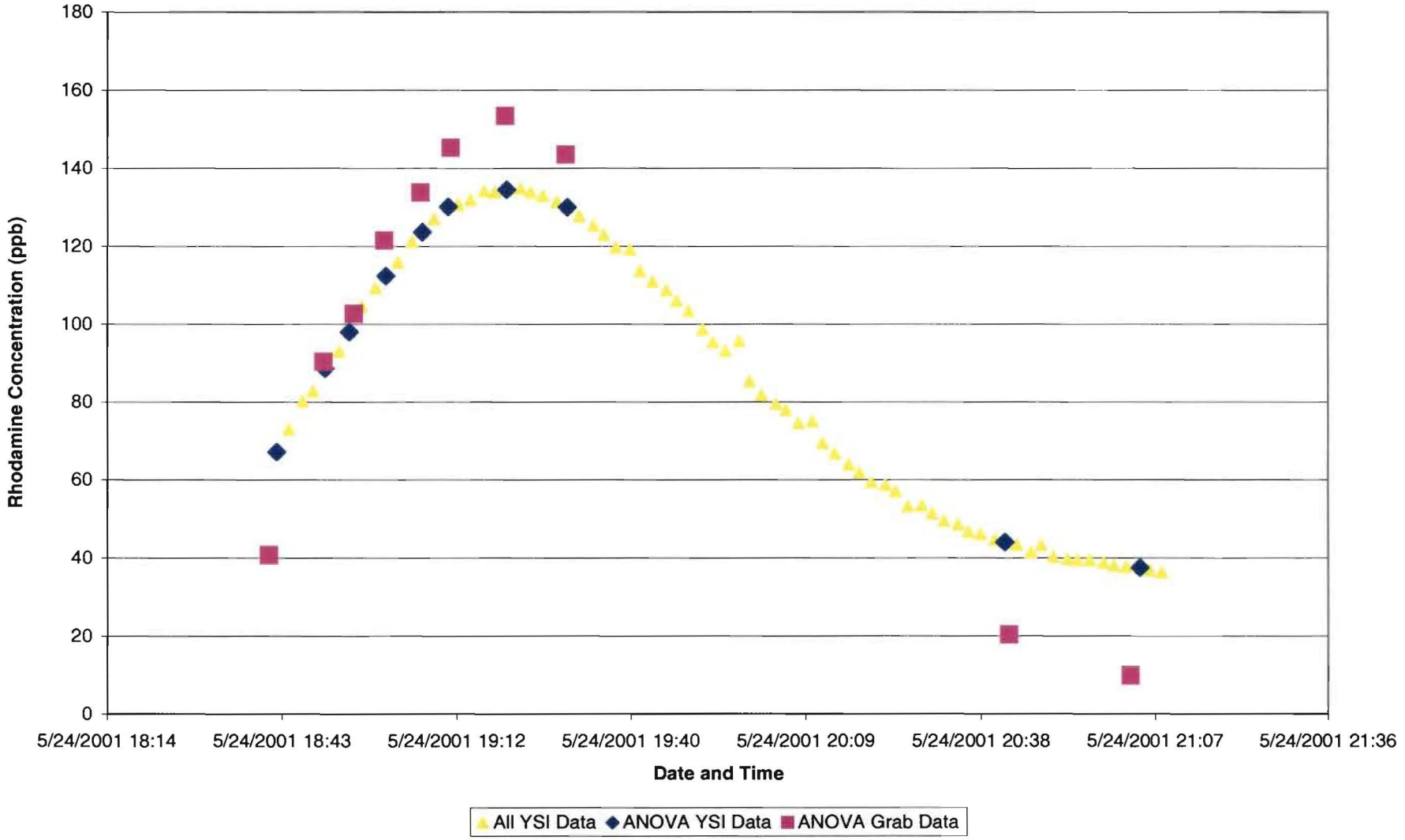
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Watkins Road (Injection at Mock Road)



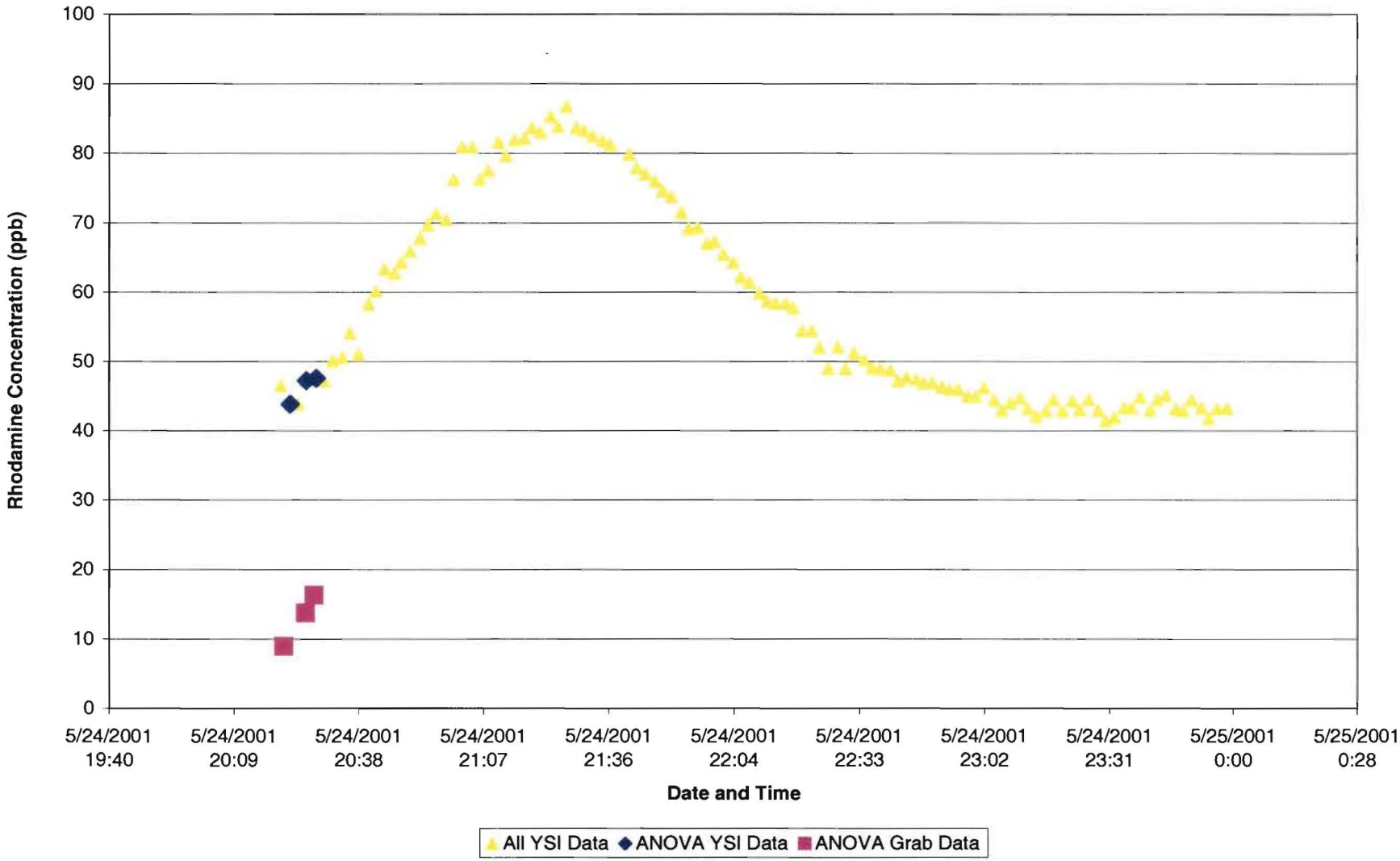
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Williams Road (Injection at Mock Road)



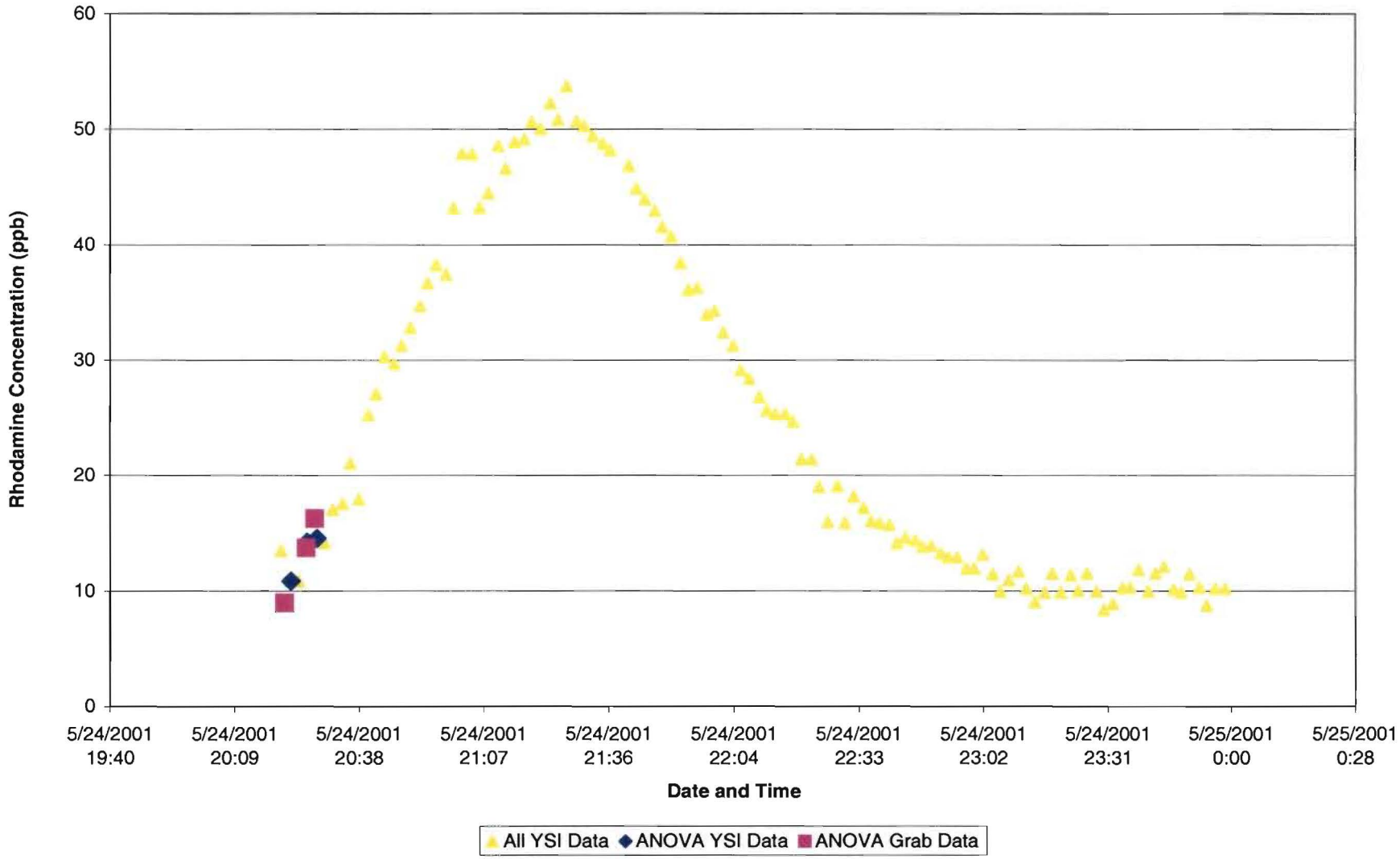
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Williams Road (Injection at Mock Road)



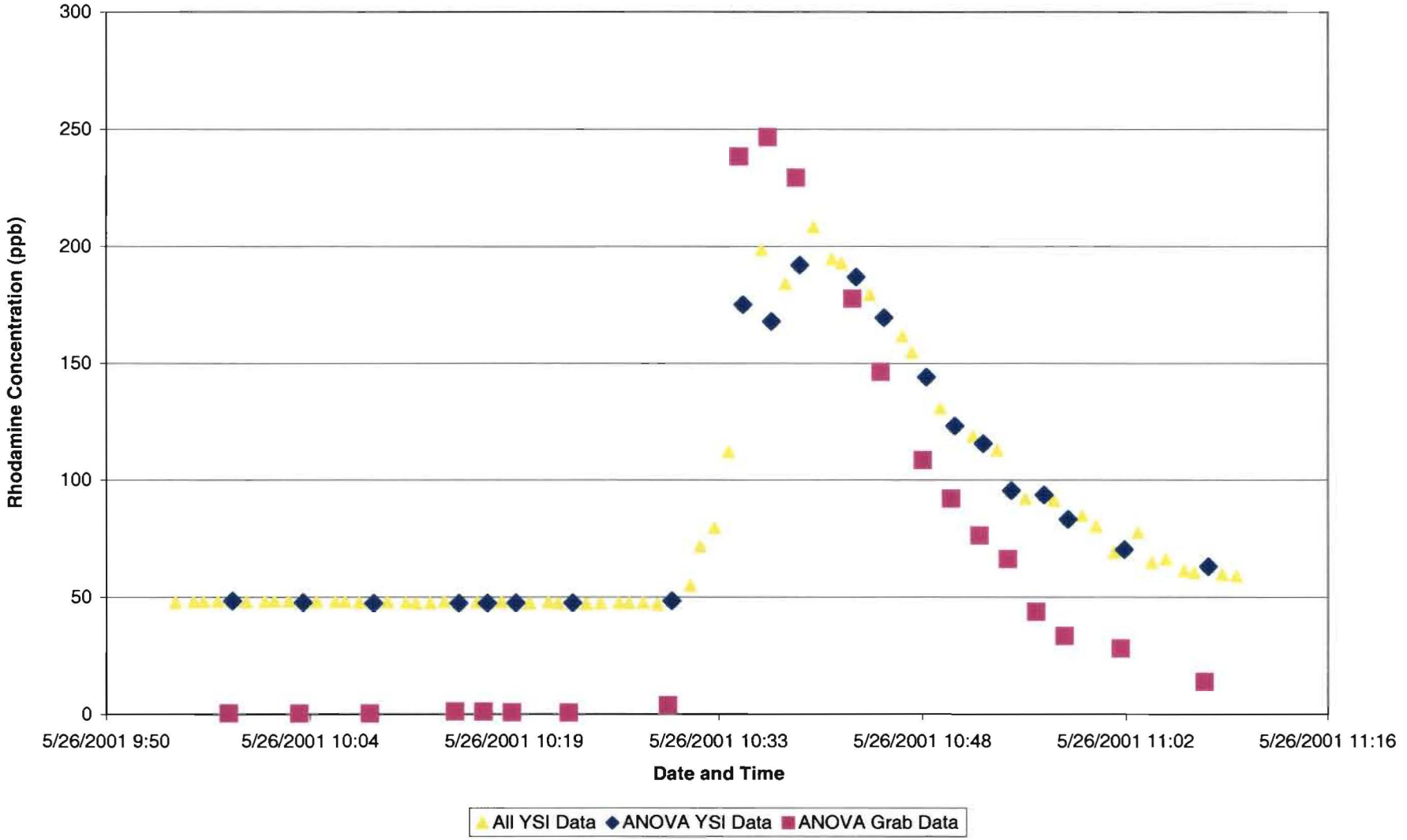
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Groveport Road (Injection at Mock Road)



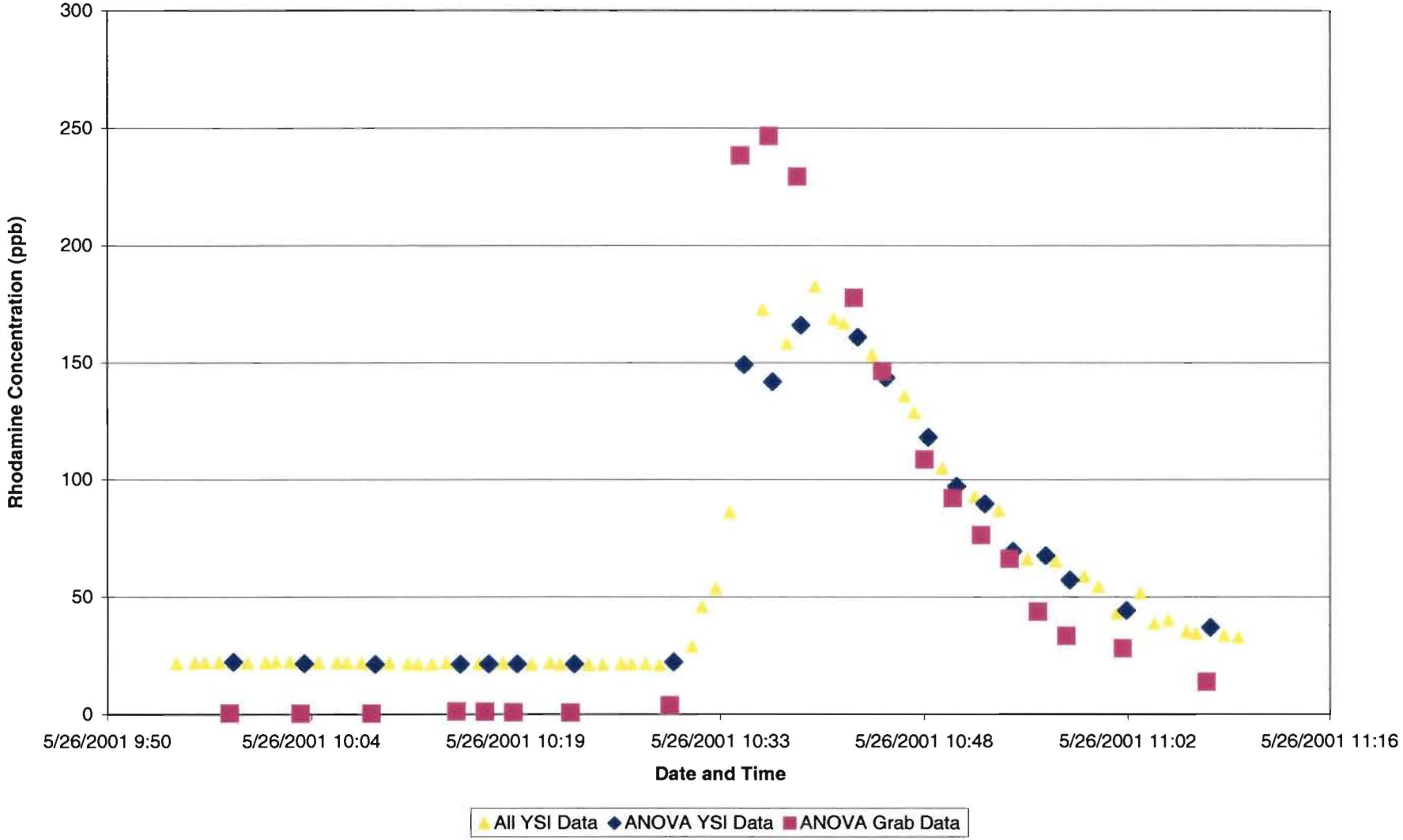
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Groveport Road (Injection at Mock Road)



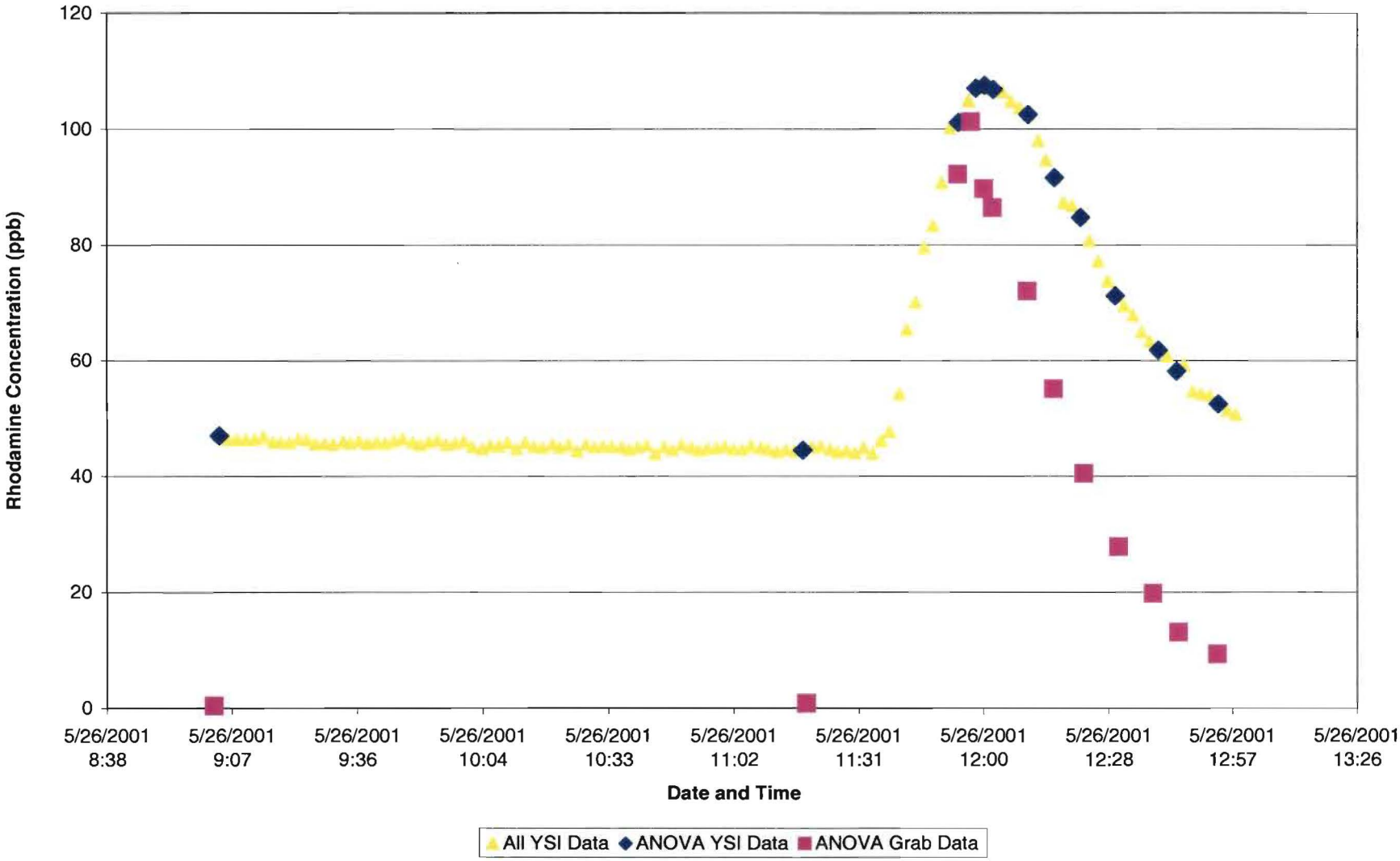
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Groveport Road (Injection at Three Rivers Footbridge)



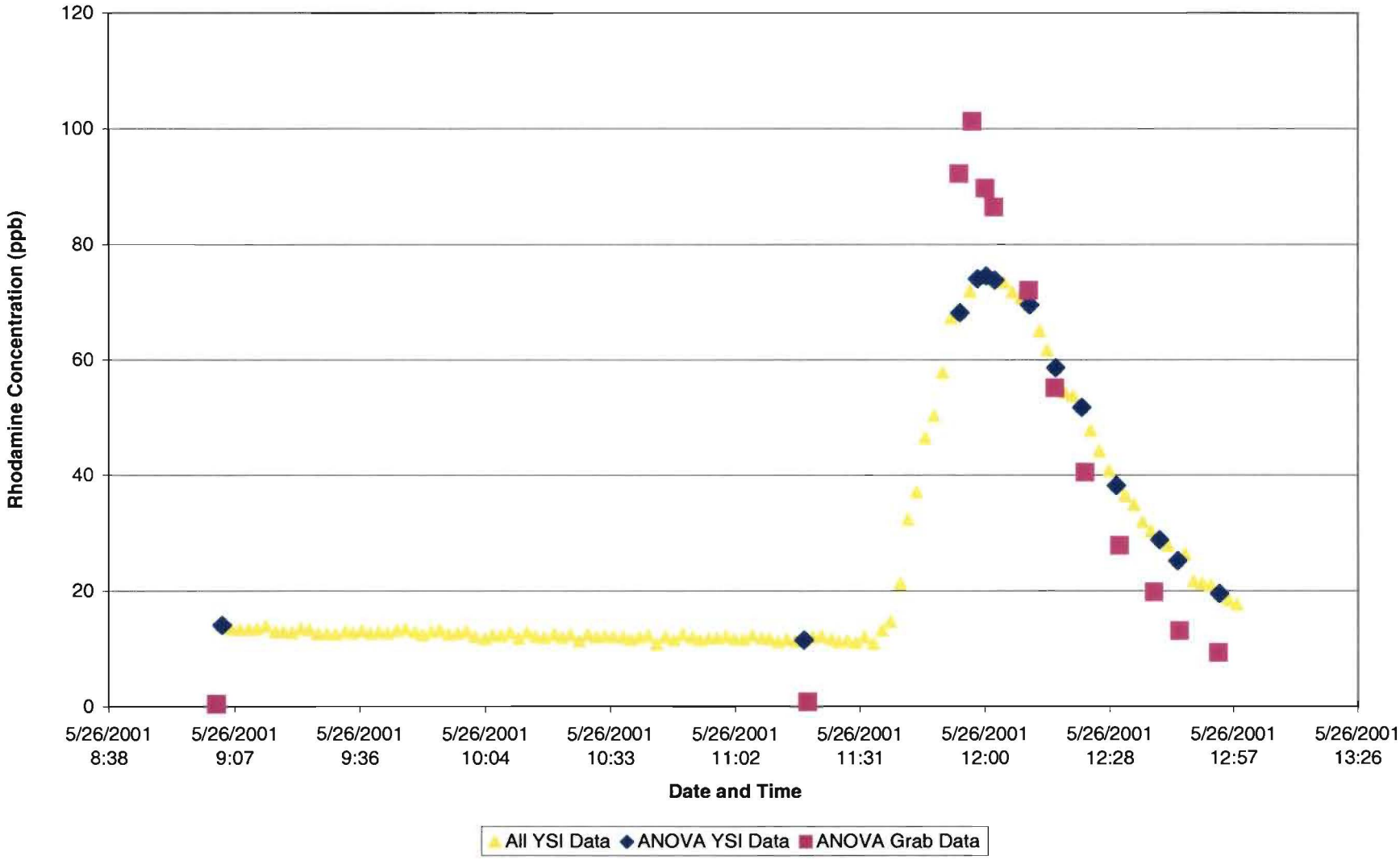
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Groveport Road (Injection at Three Rivers Footbridge)



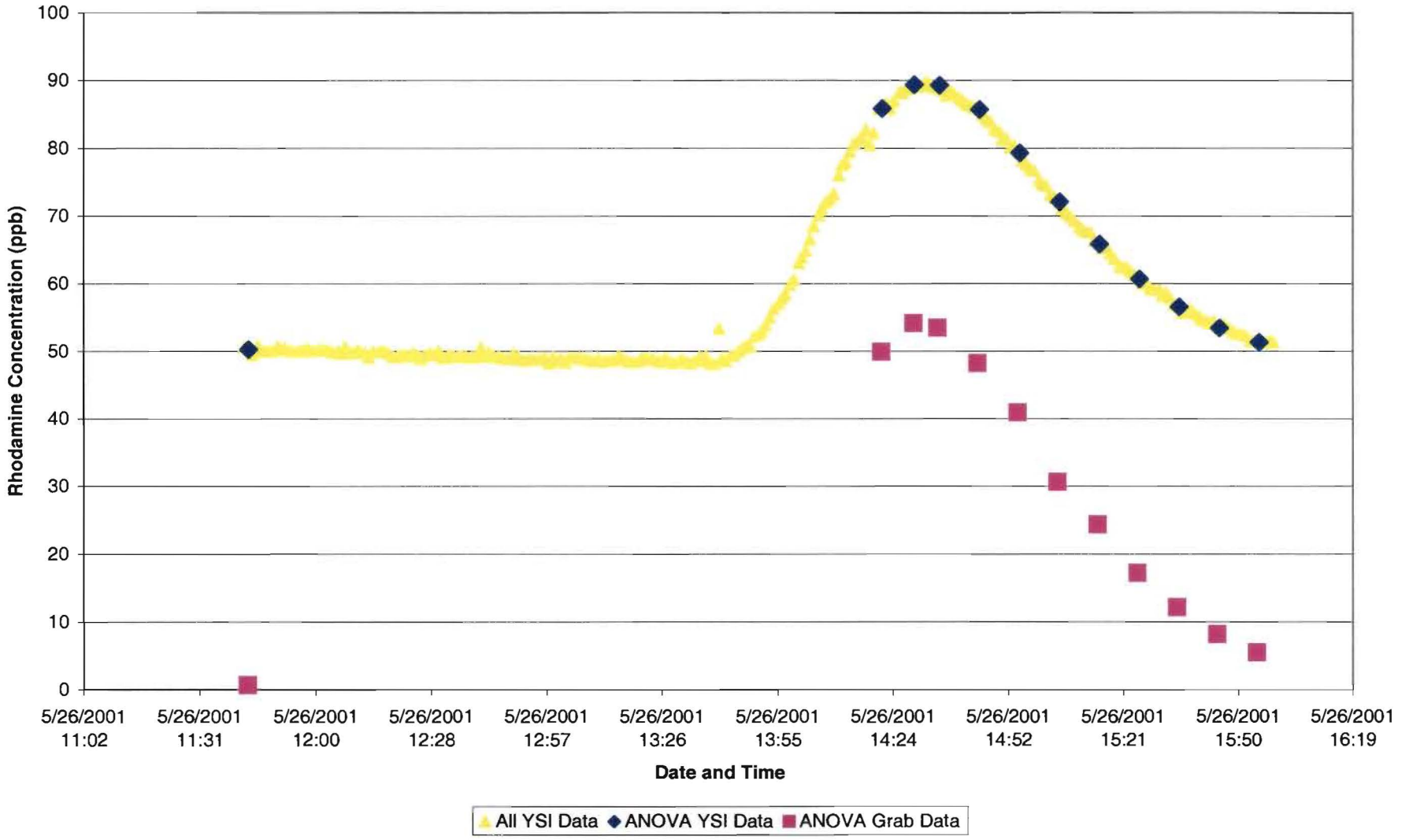
Appendix C Wet Weather Data
Pre-Background Subtraction Curve at Reese Road (Injection at Three Rivers Footbridge)



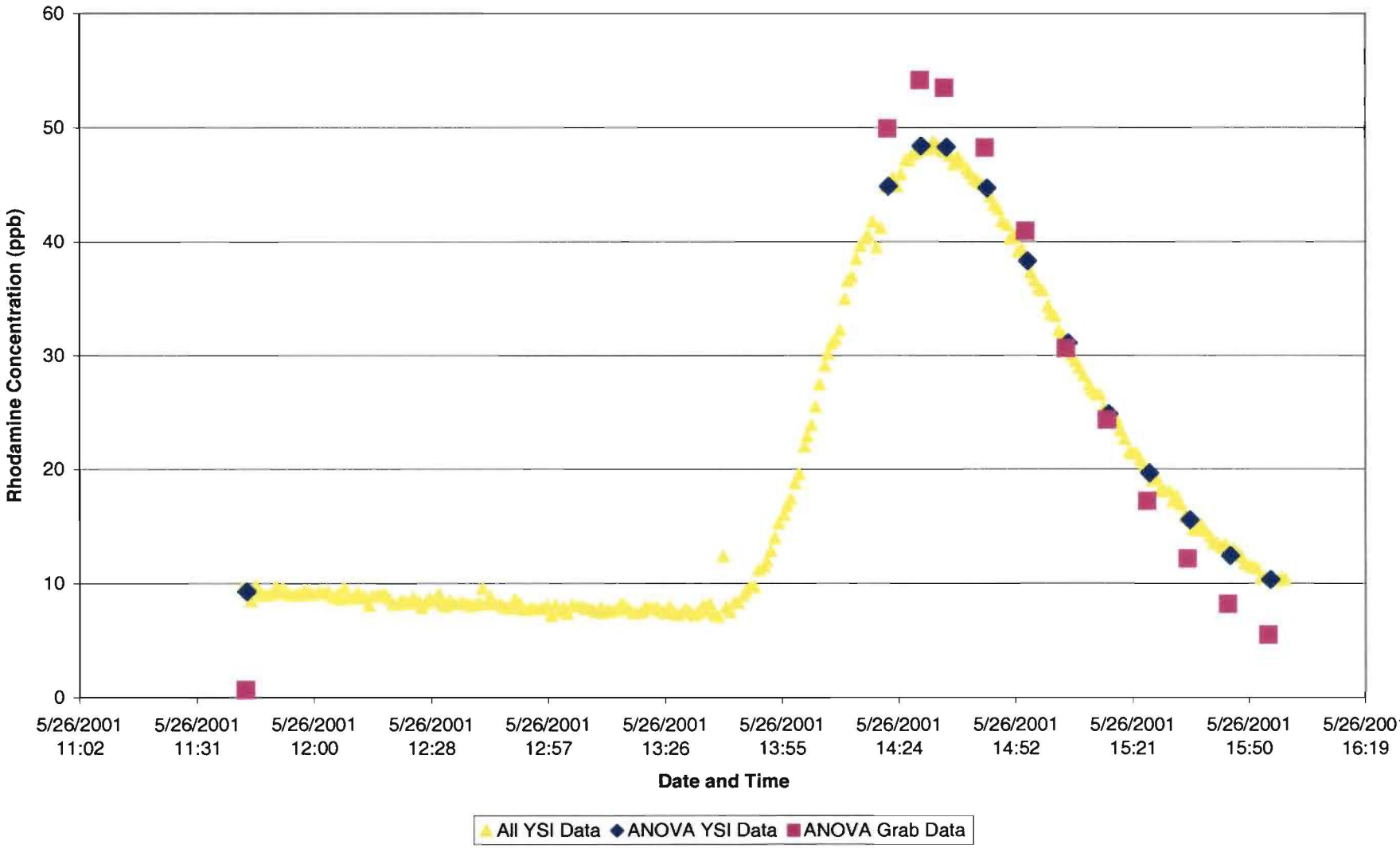
Appendix C Wet Weather Data
Post-Background Subtraction Curve at Reese Road (Injection at Three Rivers Footbridge)



Appendix C Wet Weather Data
Pre-Background Subtraction Curve at S.R. 317 (Injection at Three Rivers Footbridge)

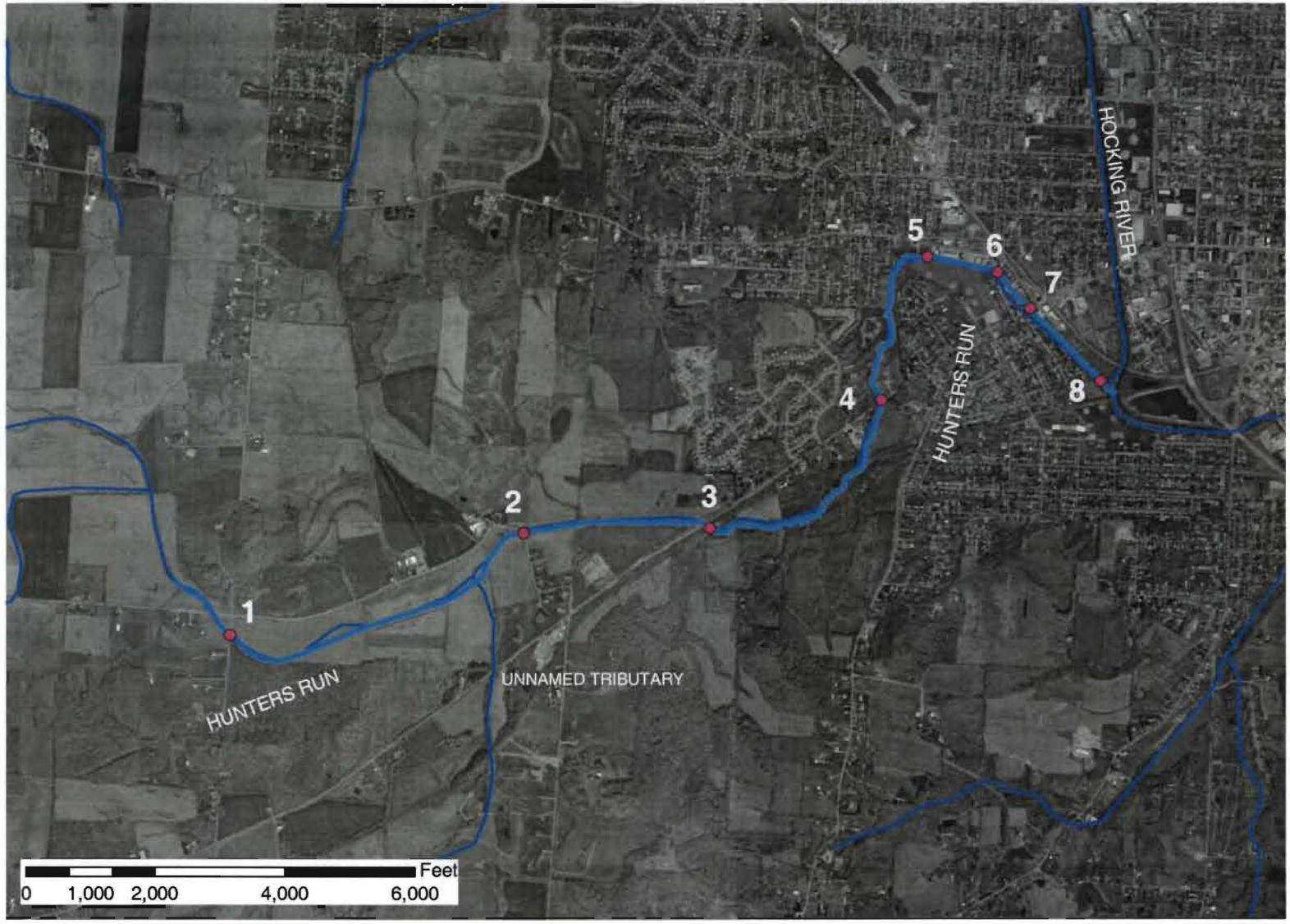


Appendix C Wet Weather Data
Post-Background Subtraction Curve at S.R. 317 (Injection at Three Rivers Footbridge)



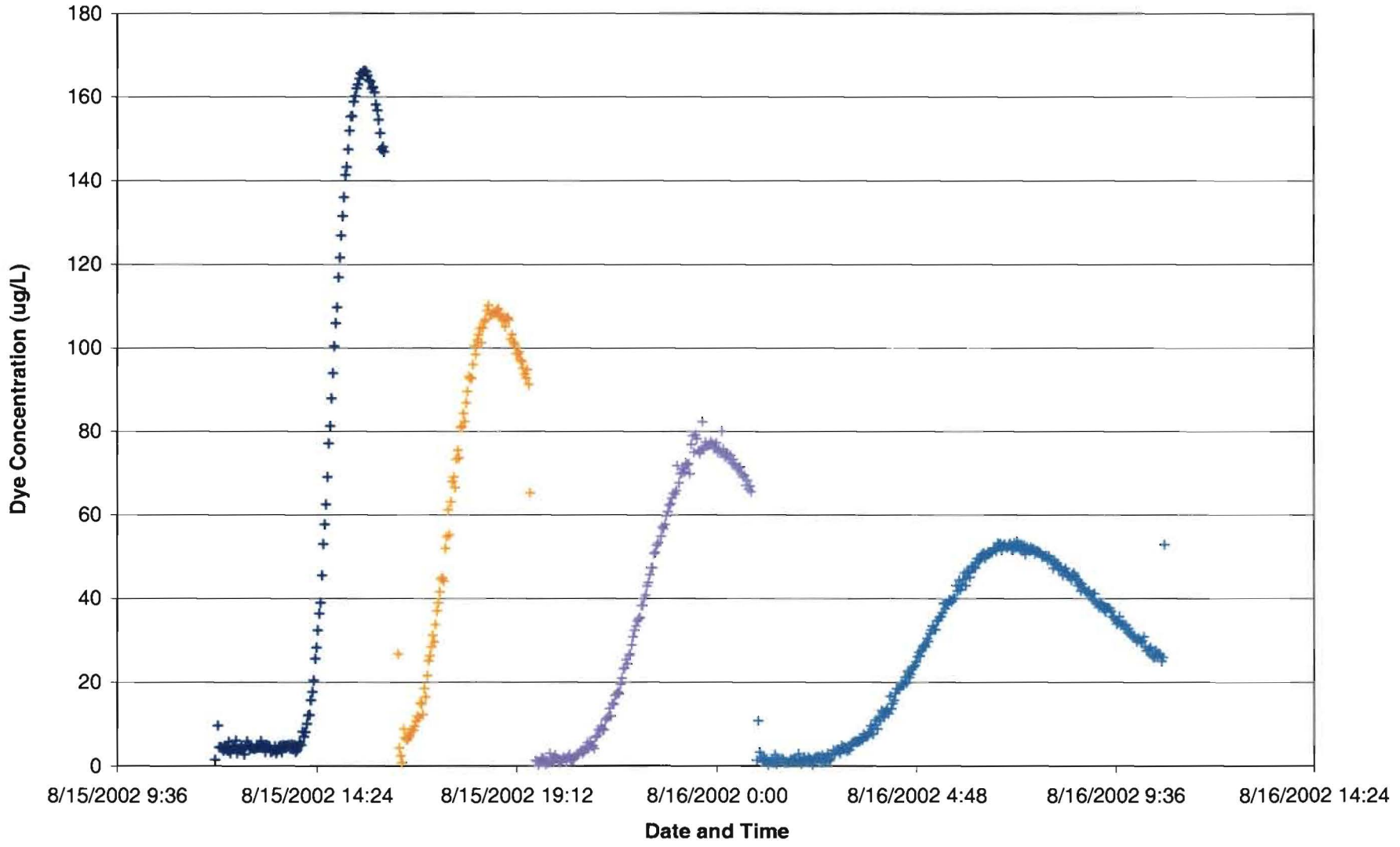
Appendix D

Further Studies – Lancaster Data



	CITY OF LANCASTER LANCASTER, OHIO APPENDIX D	CITY OF LANCASTER MAP OF TIME OF TRAVEL INJECTION AND SAMPLING SITES	FIGURE D-1

Appendix D Further Studies - Lancaster Data
YSI Rhodmamine Sensor Data for Lancaster Wet Weather Dye Study



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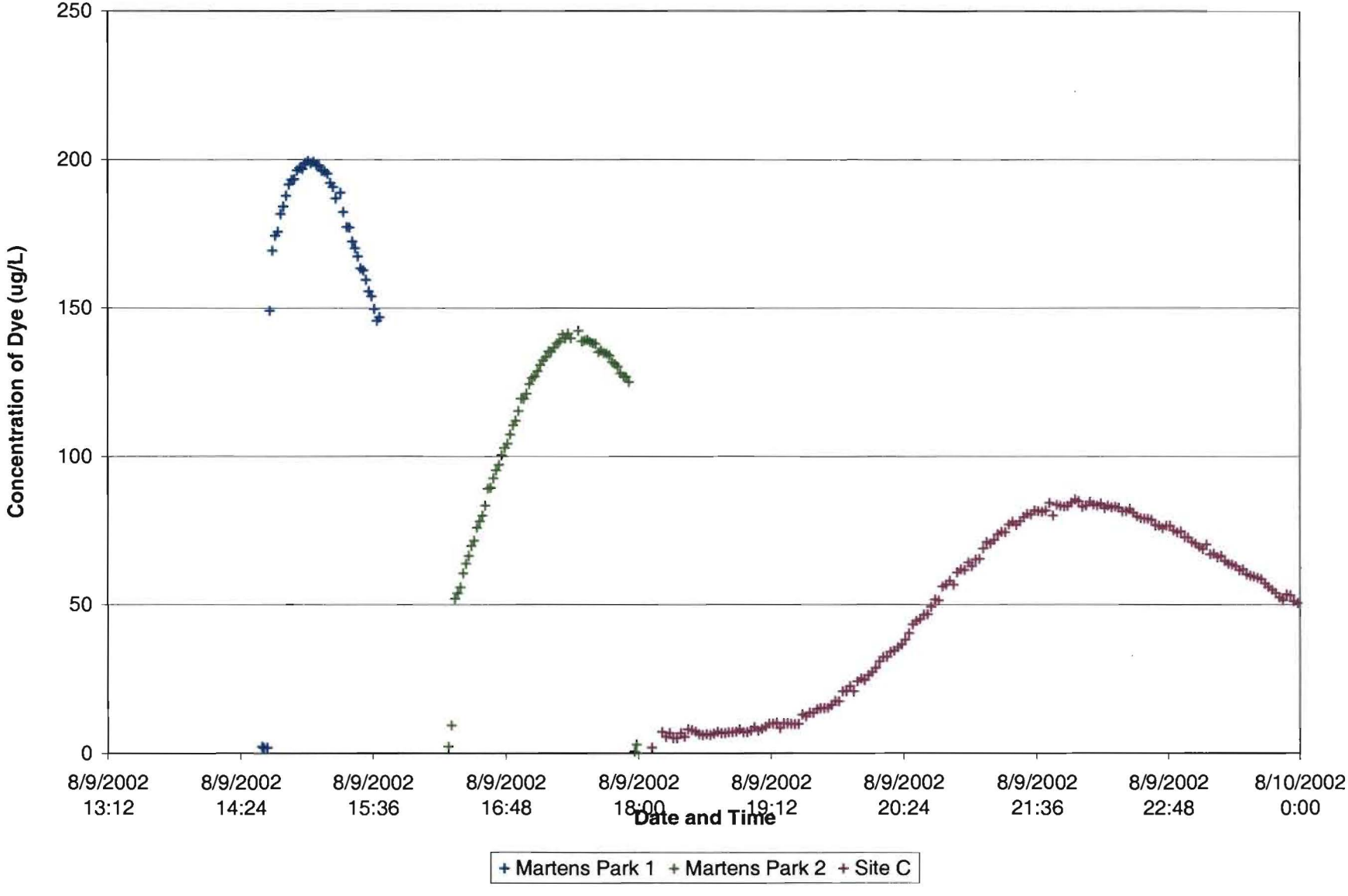
Appendix D Further Studies - Lancaster Data
YSI Rhodmamine Sensor Data for Lancaster Dry Weather Dye Study



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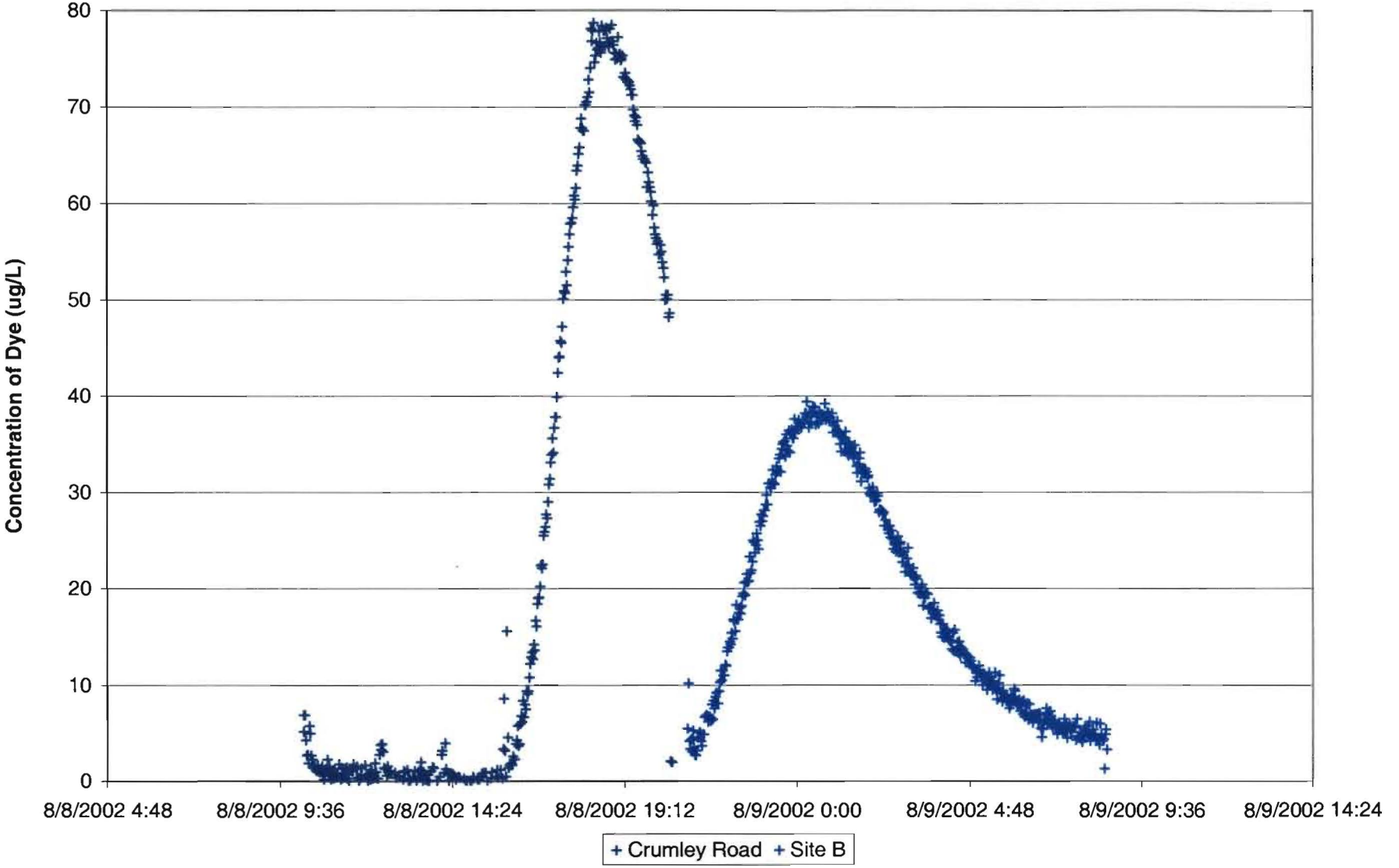
Appendix D Further Studies - Lancaster Data
YSI Rhodmamine Sensor Data for Lancaster Dry Weather Dye Study



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